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Hybrid-Electric Vehicle Technology

Policy Implications of Hybrid-Electric Vehicles

Final Report to NREL
under Subcontract # ACB-5-15337-01

April 22, 1996

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Acknowledgements

The authors would like to acknowledge the following people for their signicant support. Doug Coleman and Robert Lewit were instrumental in developing the computer simulation model for assessing vehicle system emissions. Cheryl Smith, Tao Tang and Lan Tang contributed substantial administrative support that is critical for the successful completion of a report of this magnitude. Keith Wipke and Terry Penney of NREL were indispensible in there support of this research and their commitment to its completion. Robert Lutz and Kevin Austin offered critical review of early drafts of this report that allowed the authors to make substantial improvements in the report. Finally, the authors would like to thank the National Renewable Energy Lab for their financial support that made this report possible.

The authors accept full responsiblity for any errors or omissions in this report.

Abstract

Properly-designed hybrid-electric vehicles (HEVs) using today's production vehicle platforms could offer the consumer, in the near-term, an affordable and appealing alternative to conventional ICE-powered (internal combustion engine) vehicles. At the same time, these vehicles could achieve the national priorities of reduced fuel use and reduced emissions.

Based upon the study results, half of all personal autos on the road in the U.S. on a typical day travel less than 20 miles. These vehicles represent less than 20% of the total miles driven, but, due to cold engines and cold catalytic converters, these short trips produce more than 40% of all the emissions.

An HEV with a low-cost, light-weight battery pack and a small engine-powered auxiliary power unit (APU) could plug in to any 110 V (or 220 V) outlet at night and travel these short daytime trips on battery power alone. On longer trips, the engine/alternator could augment the battery and maintain the battery charge. By refueling every 400 miles like a conventional vehicle, trips of unlimited length are possible.

Because such HEVs could be used on all trips, the initial miles of every day's travel would be on electricity. BOEVs, on the other hand, could be used only on trips within battery range. On longer trips, the driver would need to use a conventional vehicle.

Based upon this "driver-level" analysis and using nation-wide travel statistics from the 1990 National Personal Transportation Survey," the study reveals that two HEVs with only a 15-mile battery range would travel, on average, more annual miles on electricity than one 100-mile battery-only electric vehicle (BOEV). On longer trips, such HEVs with finely-tuned APUs operating at steady load are likely to operate with much lower emissions than comparable ICE-powered conventional vehicles. Because of these benefits, the report argues that such HEVs should be accorded ZEV (zero-emission vehicle) credit on the basis of their ability to "electrify miles."

HEVs could offer the same performance, range and "full-tank" feeling of security as conventional vehicles. Yet they are likely to cost less than BOEVs. In mass-production, such

HEVs might compete in cost with conventional ICE-powered vehicles. Under those circumstances, such HEVs could gain significant and perhaps dominant market share.

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Executive Summary

Policy Implications of Hybrid-Electric Vehicles

Conventional motor vehicles powered by internal-combustion engines (ICE) pose substantial economic, environmental and energy security issues for the U.S. and, increasingly, for all nations. This report analyzes the significant benefits that hybrid-electric vehicles (HEVs) offer in addressing these issues.

Contrary to the image of long daily trips by most American drivers, fully half of all personal automobiles on the road travel less than 20 miles on a typical day.[1] While they account for only 15% of all miles traveled, they account for half of all engine "cold starts." Thus, these short-mileage vehicles produce far more emissions than their total miles driven would suggest. However, emissions and fuel use on these short-mileage trips can be reduced or eliminated by using vehicles that can travel on electricity from the electric utility.

A "series" HEV is one technology that can "electrify" these short trips while also offering long-range capability and quick-refueling convenience using the existing conventional-fuels infrastructure. This report's baseline series HEV incorporates an electric motor/controller, a light-weight, low-cost, high-power battery pack and a small, fueled engine that drives an alternator as an auxiliary power unit (APU). The vehicle is plugged in at night,[2] and local trips are accomplished solely on batteries. Trips beyond the range of the batteries are accomplished using the APU to augment the battery and maintain battery charge. Trips of unlimited length are possible by refueling every few hundred miles like a conventional vehicle.

Three separate technology scenarios (battery-only EVs (BOEVs), HEVs, and advanced conventional vehicles (ACVs)) are compared for fuel consumption, electricity use and emissions. To estimate relative benefits accurately, the analysis is undertaken at the "driver-level." In the BOEV scenario, drivers use a BOEV for all short trips and an ACV for trips beyond the range of the BOEV. In the HEV scenario, HEVs are used for all trips; short trips are accomplished on battery power alone, and on longer trips the initial miles each day are on battery power and the final miles are on fuels. The 1990 Nationwide Personal Transportation Survey (NPTS) is used as the data base for daily personal automobile use.

The results indicate that HEVs would offer a dramatic reduction in fuel use in two ways, 1) by using utility electricity to charge the HEV's battery pack and 2) from greater fuel-efficiency when running the APU. Thus, an HEV with only a 15-mile battery range and 55-mi/gal fuel economy when using the APU would displace, on average, 69% of fuel from today's (27.5 mi/gal) levels. Such an HEV would displace as much fuel as the PNGV[3] target of an 80-mi/gal vehicle.

To compare the use of electricity by HEVs and BOEVs, a 100-mile battery-range BOEV at a 10% market share (California's regulatory target for 2003) is simulated as the baseline. By comparison, an HEV with only a 15-mile battery range would electrify, on average, the same number of miles at 19% market share. In other words, two 15-mile HEVs would electrify, on average, more miles than one 100-mile BOEV.

In reducing emissions, BOEVs and HEVs are significantly superior to ACVs because both HEVs and BOEVs can "electrify miles." Furthermore, HEVs with APUs that operate only at their ideal operating points can produce much lower emissions than ACVs with engines that must respond to rapidly changing requirements for power. The report describes the conditions under which drivers using HEVs for all trips would lower emissions further than drivers using BOEVs for short trips and ACVs for long trips.

In addition to their reduced emissions and reduced fuel use, HEVs offer the high performance, unlimited range, and "full-tank" feeling of security that drivers now have in conventional vehicles but not with BOEVs. Hence, HEVs may broaden the market beyond the demand for BOEVs alone. This larger market would enable higher production levels and lower per-vehicle costs for both HEVs and BOEVs. This could result in a greater market penetration of both HEVs and BOEVs with correspondingly greater benefits (reduced emissions, reduced fuel use and increased use of night-time electricity) than would be possible with BOEVs alone.

For these reasons, regulations, R & D initiatives and financial incentives need to be consistent with these benefits to create a "level-playing field" for all vehicle-fuel systems. To this end, the California Air Resources Board (ARB) staff has proposed that HEVs be certified for ZEV (zero emission vehicle) credit in proportion to their battery range, that is, in proportion to their ability to electrify miles. The ARB also has proposed a new vehicle category defined as Equivalent Zero-Emissions Vehicle (EZEV). An EZEV would have per-mile emissions no higher than the pro-rated emissions from the power plants in Southern California that would provide electricity for BOEVs. Such vehicles would be accorded full ZEV credit under the new proposed regulations.

The report argues that two additional principles derive from this EZEV category and should guide the drafting of regulations and the interpretation of the ZEV mandate.

1) EZEVs could be considered the "baseline" ZEV to which all other technologies are compared. If EZEVs (like ACVs) are not range-limited, they can be used on all trips, regardless of trip length or total daily miles traveled. Thus, in terms of emission reductions, these EZEVs are equivalent to "electrifying" 100% of the miles driven by the driver.

2) "Percentage of miles electrified" is useful in assessing all technologies under the ZEV mandate. Thus, the amount of ZEV credit granted to BOEVs and HEVs should be in proportion to the "percentage of miles electrified." This principle also can serve as the baseline from which to apply multipliers for the early introduction of advanced technology.

The report also addresses additional limitations associated with the emissions regulations and concludes with proposals for analysis that would clarify some key outstanding issues.

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[1] 1990 Nationwide Personal Transportation Survey (NPTS).
[2] Any 110 V (or 220 V) outlet would be satisfactory. The electric utilities have ample night-time capacity.

[3] Partnership for a New Generation Vehicle, the joint effort by the US government and GM, Ford and Chrysler to develop an 80-mi/gal 5-6 passenger automobile. The 55-mi/gal goal is to be achieved from regenerative braking, efficient energy storage and improved efficiency of the engine and motor/controller.

Introduction

Conventional motor vehicles pose substantial economic, environmental and energy security issues for the U.S. and for most of the industrialized world. Furthermore, as developing nations introduce increasing numbers of conventional vehicles into their economies, these issues will be exacerbated. This report analyzes the potential of hybrid-electric vehicles (HEVs) to address these problems. The report is organized into nine sections. Section I outlines the economic, environmental and energy security problems created by today's automobiles. Section II analyzes how personal automobiles are driven each day to better understand the source of these problems. Section III describes the series HEV that serves as the baseline vehicle for assessing the potential of HEV technology to ameliorate these problems. Section IV compares the exhaust emissions impact of the baseline HEV, advanced conventional vehicles (ACVs) and battery-only electric vehicles (BOEVs). Section V discusses the issue of full-cycle emissions. Section VI compares the same three technologies in regards to energy use. Section VII explores the potential impact of other HEV configurations on emissions and fuel use as compared with the baseline series HEV. Section VIII discusses the policy implications of HEVs given their potential to dramatically reduce emissions, fuel use and the trade deficit. Section IX outlines areas for further study. Please see the Glossary for a list of acronyms used in this report.

I. Economic, Environmental and Energy Security Issues Posed by the Automobile

Motor vehicles are both an essential element in today's transportation system and the source of major environmental degradation and economic and political risks. Petroleum imports for transportation account for 50% of the U.S. trade deficit and create significant economic costs and political risks for the U.S. The inability to meet metropolitan ozone standards is driving regulations that demand lower motor vehicle emissions. The perceived threat of global warming has resulted in concerns regarding the CO_2 emissions from motor vehicles. The U.S. Office of Technology, in its 1995 "Assessment of Advanced Automotive Technology," concluded that:

> *". . . it is clear that a major advance in automotive technology that could dramatically reduce gasoline consumption and emissions would have great national and international benefits. Such benefits would include not only the direct cost savings from reduced oil imports (each 10 percent drop in oil imports would save about $10 billion in 2010) but also indirect savings such as:*
>
> - *health benefits of reducing urban ozone concentrations, now estimated to cost $0.5 billion to $4 billion per year;*
> - *an "insurance policy" against sudden oil price shocks or political blackmail, the risk of which is estimated to cost $6 billion to $9 billion per year;*

- *reduced military costs of maintaining energy security, which according to some estimates costs the United States approximately $0.5 billion to $50 billion per year;*
- *potential savings from reduced oil prices resulting from decreased oil demand, conceivably tens of billions of dollars per year to the U.S. economy, and more to other oil-consuming economies; and*
- *increased leverage on the climate change problem, whose potential costs are huge but incalculable.*

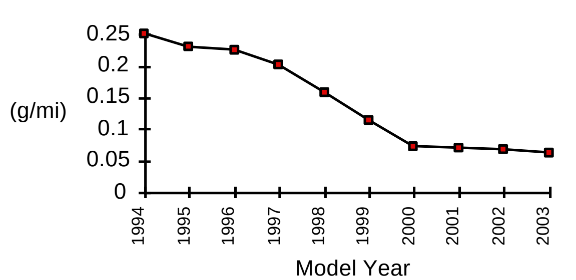
Furthermore, if U.S.-developed advanced automotive technology were to penetrate not only the U.S. market but also the markets of other developed and developing countries, the benefits to the environment and the U.S. economy would multiply.” (Ref. 1)

Since the 1960’s, increasingly stringent automotive emissions standards have reduced per vehicle pollution 94%[1] in new vehicles, but air quality problems persist. Historically, California has led the U.S. and the rest of the world in tightening automotive emission standards. Six of the seven cities with the worst ozone problems in the United States are located in California.[2] Thus, the U.S. government has allowed California to set its own more stringent standards for automotive emissions. All other U.S. states have the option of enforcing either California or Federal standards.

The California Air Resources Board (ARB) reported in 1990 that cleaner running cars have “. . . *improved air quality in some areas of California and slowed the deterioration in others. However, further reductions in vehicle emissions are needed to offset the continuing increase in vehicle use*.” (Ref. 4). Thus, the ARB’s 1990 Low-Emissions Vehicles and Clean Fuels regulations (Ref. 4) require greater emissions reductions in new conventional vehicles. Figure 1 outlines the declining fleet average NMOG (non-methane organic gas) standard and the vehicle standards that auto manufacturers must meet to comply with the fleet standard.

Figure 1 - California Automobile Emission Regulations

Fleet Average NMOG Standards for Passenger Cars and Light-Duty Trucks <3750 Lbs



Source: 1990 ARB Staff Report (Ref. 4)

50,000 Mile Certification Standards (g/mi) for Passenger Cars Operation on Gasoline

CATEGORY	NMOG*	CO	NOx
Adopted for 1993	0.25	3.4	0.4
TLEV	0.125	3.4	0.4
LEV	0.075	3.4	0.2
ULEV	0.040	1.7	0.2
EZEV (proposed)	0.004	0.17	0.02

* NMOG emissions would be reactivity adjusted for cleaner-burning fuels.

In addition to these regulations, the ARB has recognized the need to stimulate a quantum reduction in vehicle emissions in order to meet federal air quality standards in California's most polluted metropolitan areas. Thus, the ARB requires that zero emissions vehicles (ZEVs) must be 10% of auto manufacturers' product offerings in California beginning in 2003.[3]

As the ZEV regulations are now written and interpreted, the BOEV is the only technology that qualifies for ZEV credit. However, the ARB staff has drafted proposed amendments that would certify HEVs for ZEV credit based either on miles electrified or as equivalent zero-emission vehicles (EZEVs) (Ref. 5). An EZEV is defined to have full-cycle emissions that are equal to or lower than the full-cycle emissions associated with BOEVs in southern California (see Figure 1 for proposed emissions standard).[4] Section VIII discusses the policy implications of the potential benefits offered by HEVs with a particular focus on the California ZEV regulations.

The issue of automotive fuel use and petroleum imports has not received as much regulatory attention as automotive emissions. In 1978, the U.S. government instituted the Corporate Average Fuel Economy (CAFE) standard. The CAFE standard today is 27.5 mi/gal for automobiles and there is little political or regulatory action underway to change the standard.

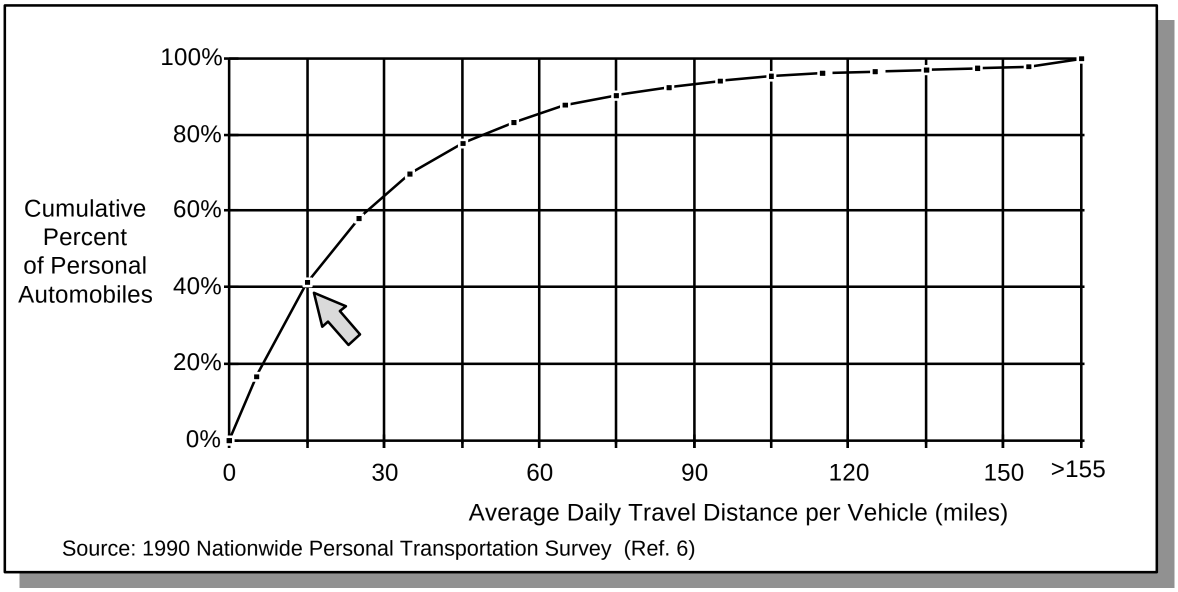
However, in 1993 the U.S. government established the Partnership for a New Generation of Vehicles (PNGV), a joint effort between the U.S. Government and U.S. auto manufacturers to pursue technology that would dramatically improve vehicle fuel efficiency. The basic underlying objective of this program is to reduce petroleum imports. PNGV has identified HEVs as among the best potential technology options to meet its goal of tripling fuel efficiency (80 mi/gal) for the standard automobile. The U.S. Department of Energy's HEV propulsion program has a target of 2X improvement in mileage (to 55 mi/gal), and this element is a significant component of the PNGV program. Section V analyzes the potential fuel use savings of HEVs, BOEVs and ACVs as well as the potential increase in the use of utility electricity.

II. Statistics of Personal Automobile Use in the U.S.

In order to assess the potential benefits of various vehicle technologies, it is critical to understand how vehicles are used. There are a variety of vehicle characteristics — type (truck, van, automobile), use (commercial, personal) — that directly influence the driving pattern of a vehicle. This report focuses on one vehicle segment, personal automobiles, to assess the benefits of HEVs. This segment was selected for two reasons. First, it is the largest market segment and, thus, has the greatest impact on emissions and fuel use. Second, automobiles are the focus of the California ZEV mandate.

To assess the potential benefits of HEVs, the 1990 Nationwide Personal Transportation Survey (NPTS)[5] is used to assess daily personal automobile use (Ref. 6). Based upon the NPTS data base, there are 123 million personal automobiles in the U.S. and 90 million are on the road on a typical day.

Figure 2 - Distribution of Personal Automobile Use by Daily Travel Distance



Contrary to the image of long daily commutes for most American drivers, the NPTS data show that, of those personal automobiles on the road, 42% travel less than 15 miles each day (see Figure 2), and less than 5% travel daily 100 miles or more.

These short mileage vehicles also account for a significant portion of cold starts. A cold start accounts for over 90% of a vehicle's HC and CO emissions on an average 8.7 mile trip because cold engines with cold catalytic converters produce much greater emissions than engines and catalytic converters operating at running temperatures (see Figure 3).

Figure 3 - Trip Emissions for a Series HEV (ULEV APU) from a Cold Start

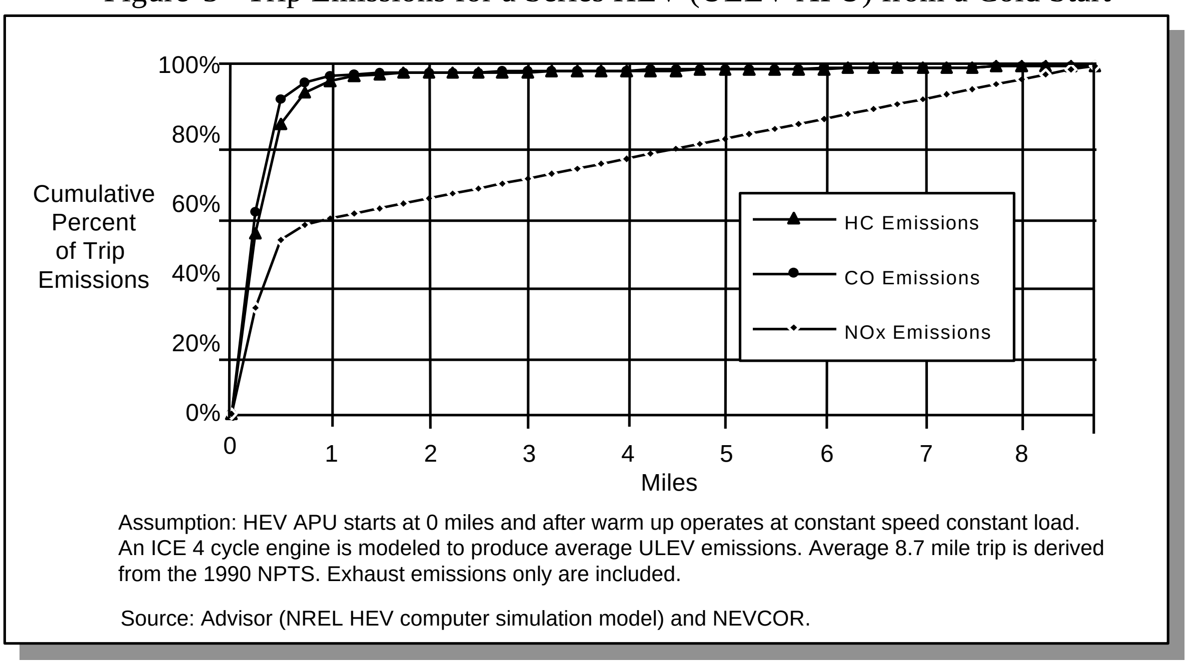
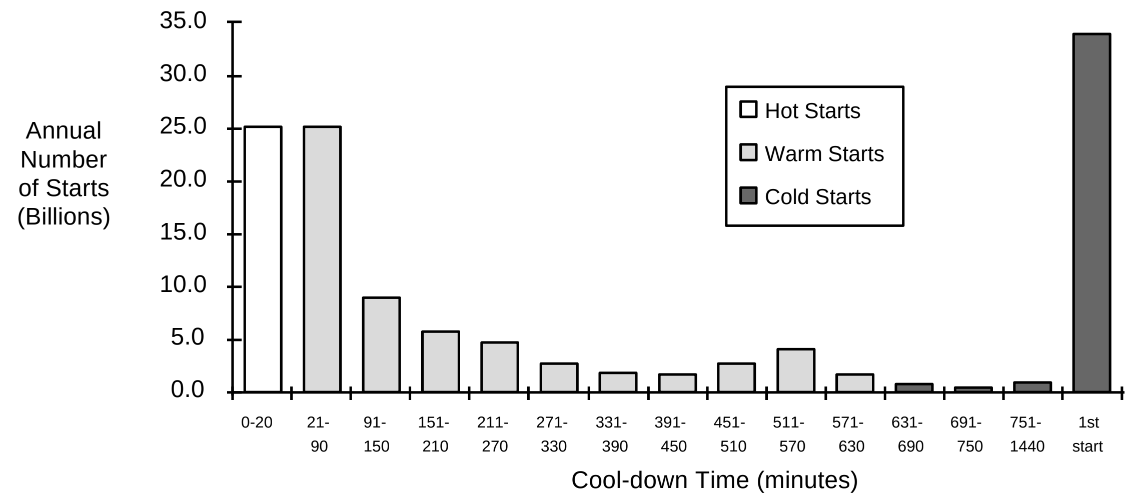


Figure 4 - Engine Cool-down Time Distribution of Personal Automobile Starts

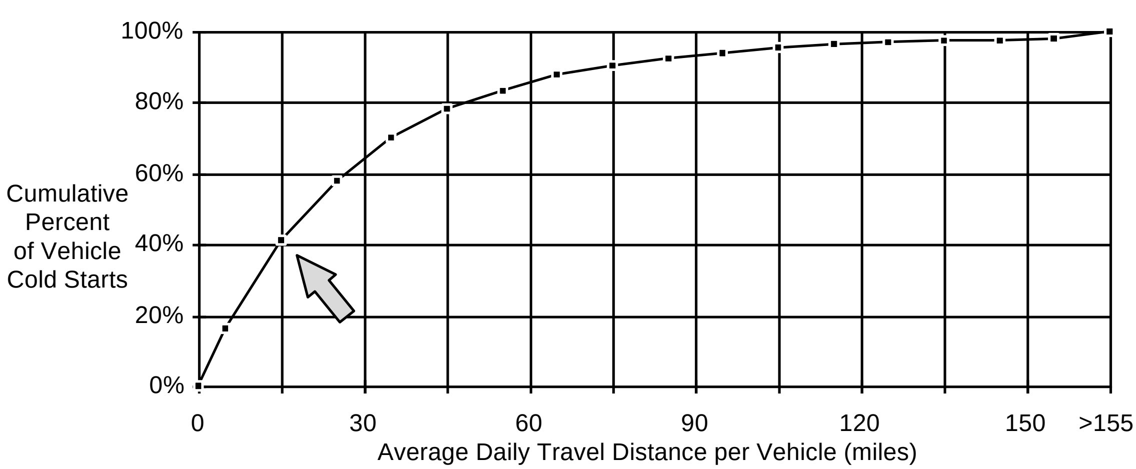


Source: 1990 Nationwide Personal Transportation Survey (Ref. 6) and NEVCOR.

Given the significance of cold-start emissions, it is critical to identify the distribution of engine starts as well as miles driven to understand the source of automotive emissions. Nationwide, there are about 35 billion cold starts out of 126 billion total personal automobile engine starts each year (see Figure 4). Appendix B provides a detailed definition of cold, warm and hot starts used in this report.

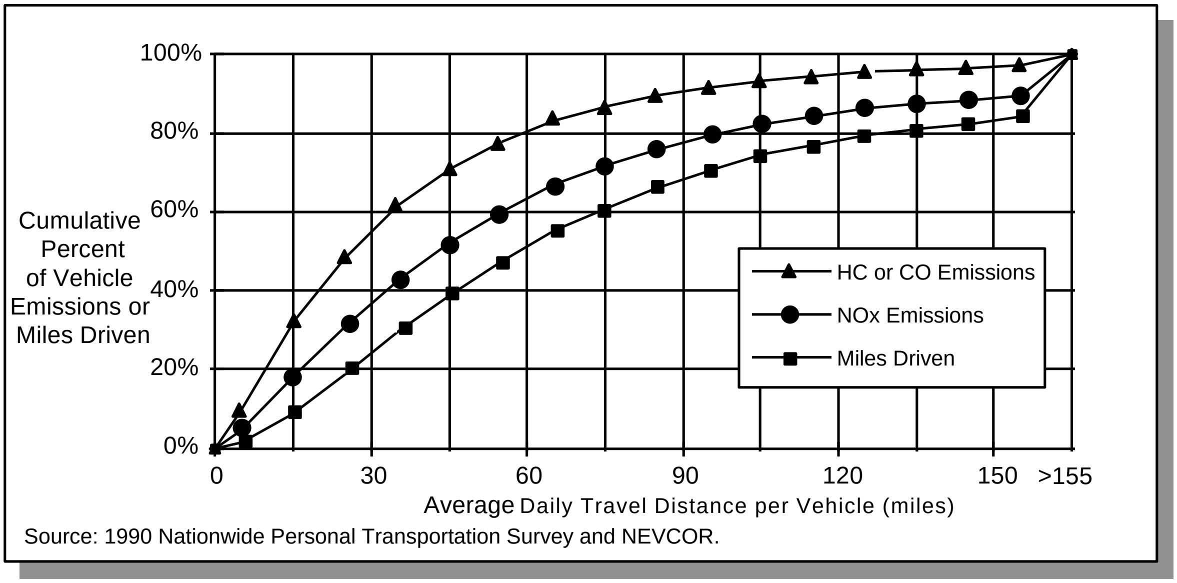
Personal automobiles that travel 15 miles or less each day account for 41% of all cold starts (see Figure 5). Due to this concentration of cold starts in short mileage vehicles, these vehicles produce disproportionately more emissions than their total miles driven would suggest. Figure 6 reveals that vehicles that travel 15 miles a day or less produce 34% of all HC and CO emissions, even though they travel only 9% of all miles traveled.

Figure 5 - Distribution of Personal Automobile Cold Starts by Daily Travel Distance



Source: 1990 Nationwide Personal Transportation Survey (Ref. 6)

Figure 6 - Personal Automobile Cumulative Miles Driven and Emissions



Appendix B provides a more detailed explanation of the vehicle system model used to compute these emission estimates

The above analysis of personal automobile use shows that there is a disproportionately large potential for emissions reduction by electrifying the short mileage trips. Furthermore, battery ranges of 15 miles are easily attainable with commercially-available lead-acid batteries and current production-vehicle platforms. However, few drivers would feel secure in a BOEV with only a 15–mile battery range as almost all of these vehicles will need to travel, on occasion, longer trips. There is wide-spread agreement that, to be widely marketable, BOEVs will require at least a 100-mile range (Ref. 7). Such BOEVs will require future advanced batteries (e.g. nickel-metal hydride) and new from-the-ground-up, light-weight, aerodynamic vehicles (such as the GM "EV-1" based on the experimental "Impact" platform). It is acknowledged that such range-limited vehicles will be more expensive than conventional vehicles and will appeal only to a niche market.

For these reasons, HEVs built on current production vehicle platforms with a relatively small, light–weight battery pack and an on–board auxiliary power unit (APU) are especially appealing. Such an HEV could electrify these short trips, and it also could travel unlimited long distances using the APU. The next section describes in more detail such an HEV.

III. Description of the Baseline "Series" HEV of this Study

The design of battery-only electric vehicles (BOEVs) has been dominated by the need to achieve the greatest possible range capability. This fixation with range has driven vehicle design and battery research, and the electric utilities have been challenged to provide a new rapid-recharging infrastructure. As one critic observed, even a 100-mile BOEV range is like starting out in a conventional car with a quarter tank of gas.

HEVs, on the other hand, typically are not range-limited, and they can be designed in a variety of ways to accomplish a variety of objectives. For example, Amory Lovins has described a concept of "hypercars," hybrid vehicles that are newly-designed from-the-ground-up to be ultra-light weight and exceptionally aerodynamic and energy efficient (Ref. 8). Such vehicles offer the prospect of very high fuel-efficiency, ultra-low emissions and the convenience of rapid refueling.

Others have reported on hybrid-electric vehicle concepts that are built on today's production vehicle platforms (Ref. 9). Such HEVs offer an early-to-market opportunity for affordable HEVs that use less far less fuel and produce far lower emissions than the ICE-powered production version of the same vehicle.

In all of these designs, the energy capacity (for battery-only range) and the power capability (for acceleration and hill climbing) of the energy storage system (e.g. batteries, ultracapacitors, etc.) play a key role in determining the vehicle's configuration, performance and cost.

This section describes an HEV design that serves as the baseline for assessing the potential benefits of HEVs. The baseline HEV design is one of the family of "series, charge-sustaining" HEVs. The baseline HEV system combines an electric motor/controller, batteries (of various range capabilities) and a small, gasoline engine that powers an electric alternator (see Figure 7). On all trips, an electric motor powers the vehicle, and the vehicle has acceleration and passing capability on battery power alone that is superior to the comparable conventional ICE-powered vehicle. The baseline HEV vehicle system also recaptures braking energy from regenerative braking.

Local trips (see Figure 8) are accomplished solely on battery-electric power with zero exhaust emissions. Recharging can be done at night when the vehicle is not operating and when electricity prices are lowest. Existing 15-20A/110V circuits could provide leisurely over-night charging for vehicles traveling up to 40–50 miles a day (that is, roughly 80% of all personal autos (72 million vehicles)). Standard 30A/220V circuits, such as clothes dryer circuits, could recharge the personal automobiles with larger advanced battery packs that travel longer trips on battery power. There would be no need for daytime charging.

Figure 7 - Baseline HEV Design

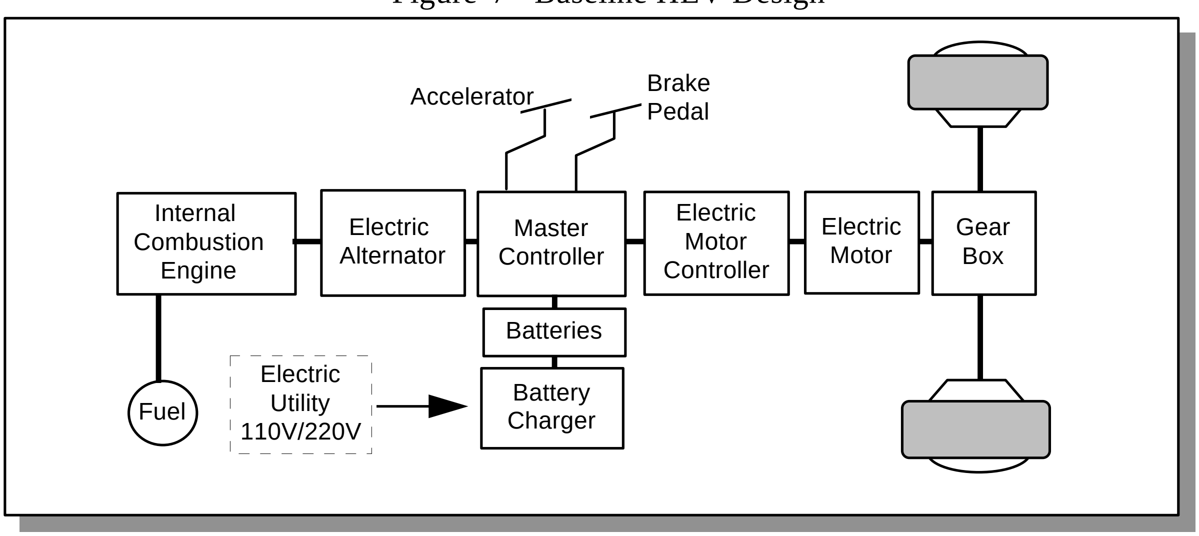
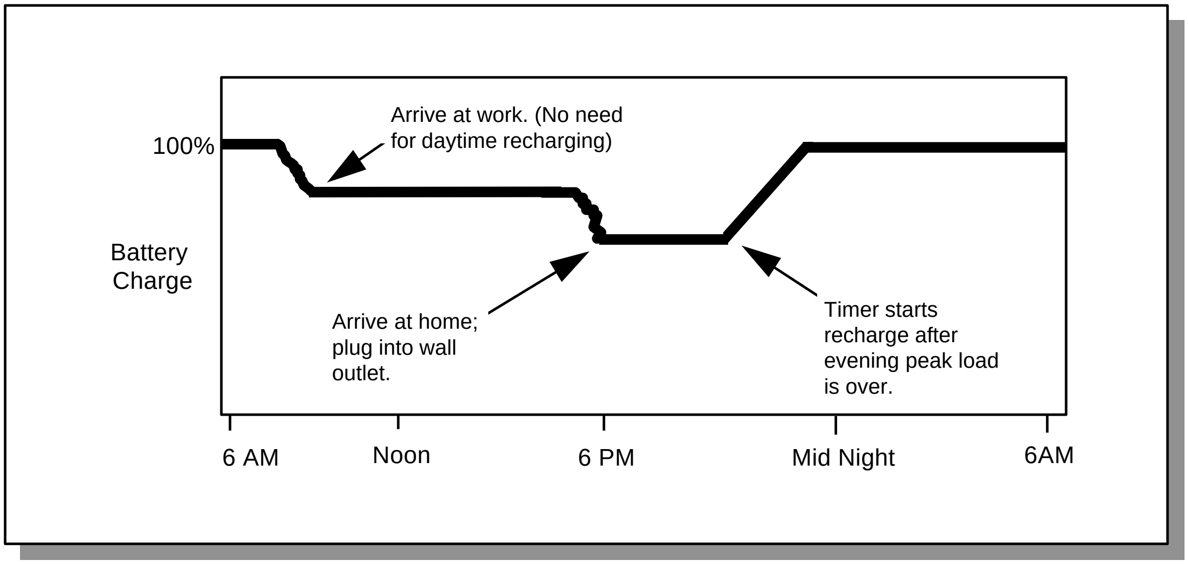


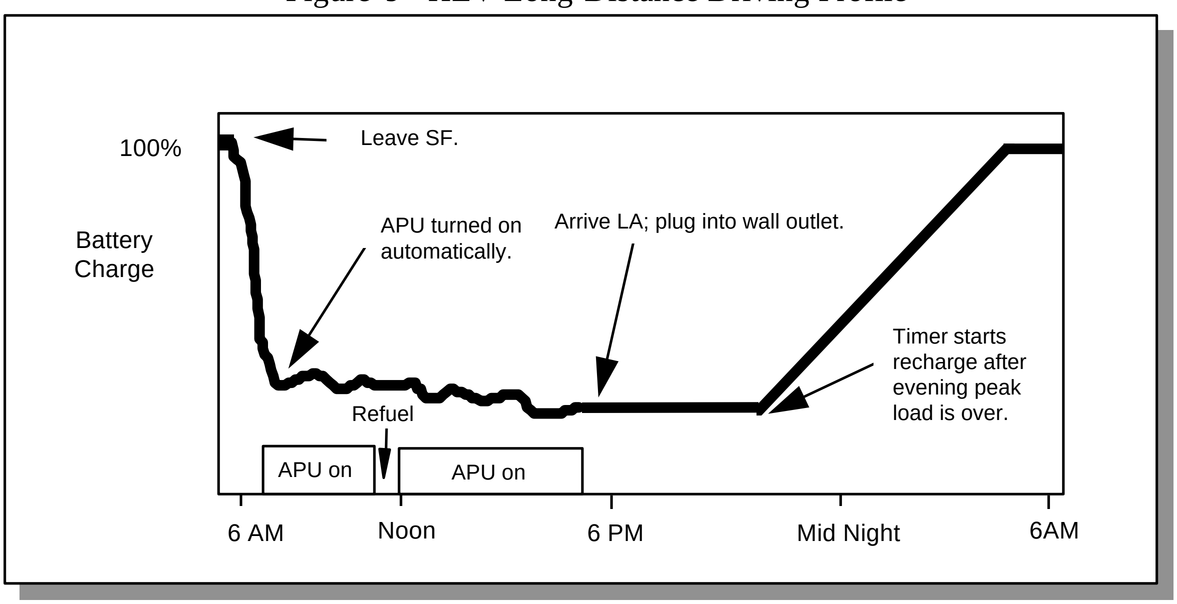
Figure 8 - HEV Urban Driving Profile



Long journeys beyond the capacity of the batteries alone, such as the 400-mile San Francisco to Los Angeles trip depicted in Figure 9, or even coast-to-coast trips, are easily accomplished using the engine-alternator to augment the battery. The engine-alternator operates at better-than ultra-low emissions in an efficient, constant-speed, constant-load mode to maintain the battery charge. The vehicle refuels every 400 miles, just like current automobiles, and it does not require any rapid recharging infrastructure.

This HEV design is analyzed in Section IV for emissions and in Section V for fuel use and electricity use, and battery range will be seen as a key parameter.

Figure 9 - HEV Long-Distance Driving Profile



IV. Exhaust Emissions

To date, regulatory authorities have specified regulations at the vehicle level to provide enforceable automotive standards. Exhaust emissions are specified in grams per mile and fuel economy in miles per gallon. Vehicle per mile and per gallon standards are used by policy makers as a suitable indicator of aggregate emissions and fuel consumption when the vehicle is in actual use by a driver.

This vehicle-level analysis methodology is acceptable when each automobile has very high task flexibility (i.e., any given vehicle can perform the vast majority of all possible missions required by the driver). Since mission flexibility continues to be one of the hallmarks of advanced conventional vehicles (ACVs), the vehicle-level analysis continues to be suitable for relative comparisons among ACVs. This vehicle-level analysis methodology also can be used for evaluation of technologies like the HEV whose mission flexibility is comparable to the ACV.

However, this vehicle-level analysis methodology yields incomplete and misleading results when applied to a vehicle such as the BOEV. The BOEV does not have the mission flexibility of the ACV, and an ACV must be used when the BOEV is unable to make a particular trip.

Therefore, the basis of analysis must be raised from the vehicle level to the driver level, thereby incorporating statistically significant differences in vehicle use patterns. In a driver-level analysis, emissions are analyzed for each driver, and the emissions are dependent on the vehicle technology used for each trip (Ref. 9). NPTS data on mission requirements (e.g., trip mileage) are used to determine how drivers would use vehicles differently. The same methodology is applied to fuel and electricity use.

The driver-level and vehicle-level analysis methodologies yield identical results when drivers use mission-flexible vehicles; however, the two methodologies yield different results when drivers use BOEVs. The limited range capability of BOEVs requires that drivers have access to other vehicles for long trips (i.e. for missions beyond the capability of BOEVs). Thus the driver must “pair” the BOEV with a mission-flexible technology such as the ACV. The HEV, on the other hand, does not have to be paired with an ACV since the HEV has the same mission capability to travel long distances as the ACV.

Using this driver methodology, three scenarios have been designed with which to evaluate three different vehicle technologies: ACVs, HEVs, and BOEVs. Each scenario highlights a single vehicle technology, and each vehicle technology is permitted to achieve its maximum possible market share nationwide in its respective scenario. These scenarios are summarized in Figure 10 and described in more detail as follows:

1) In the first scenario, all vehicles nationwide are assumed to be ACVs that operate at ULEV levels, the most stringent vehicle emission standard for conventional vehicles presently specified by California regulations (see Figure 1).

Figure 10 - Vehicle Technology Scenarios

Scenario 1	Scenario 2	Scenario 3
Advanced Conventional Vehicles (ACV)	Advanced HEV	BOEV/ACV Pair
• All daily travel is in ACVs powered by an internal combustion engine (ICE).	• The HEV is charged each night from the utility. • All daily travel within the battery-range of the HEV is traveled on battery power. • All daily travel of longer distances also is done in the HEV with the initial miles using battery power and the remaining miles using the APU.	• The BOEV is charged each night from the utility. • All daily travel within the range of the BOEV is traveled in this vehicle. • All daily travel of longer distances is traveled in ACVs powered by an ICE.

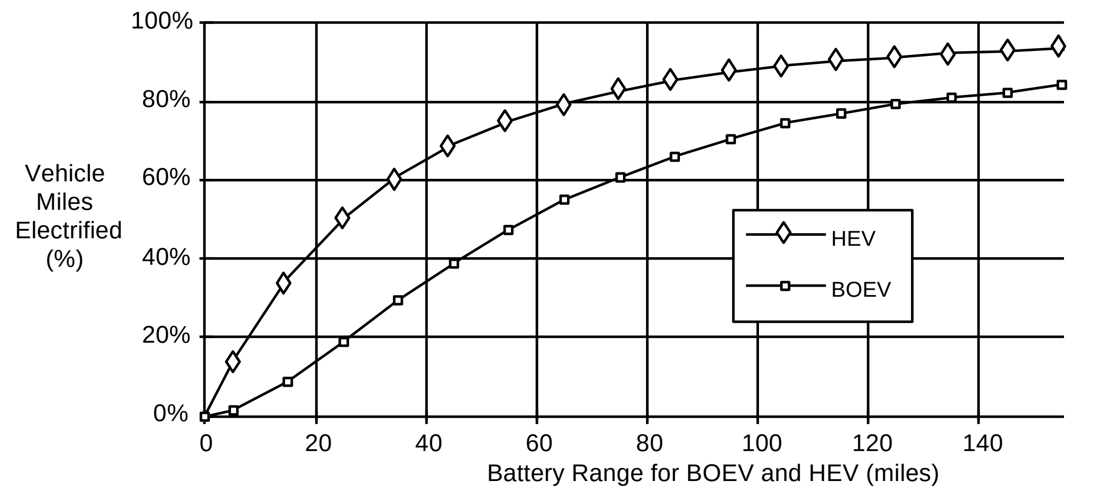
2) In the second scenario, all vehicles are assumed to be HEVs. These vehicles are a direct substitute for ACVs and meet or exceed the ACVs standards for all elements of performance, range, and refueling convenience. These vehicles recharge each night with off-peak power and drive the initial miles each day on battery power alone. If total daily trip distance is within the range of the battery, the APU will not be used. If total daily travel exceeds battery range, the remaining miles will be driven using the APU as the source of energy, and the battery will be used to provide peak power for acceleration or hill climbing or to absorb surplus power from the APU during deceleration or at stops. HEVs with APUs at "ULEV" levels are simulated to provide an "apples to apples" comparison with the ACV and BOEV/ACV pair. However, this can be considered a very cautious assumption. In a recent presentation, Mitsubishi has reported that its experimental HEV has demonstrated emissions from its APU to be at the EZEV level, that is, 10% of ULEV (Ref. 10). Thus, results also are reported in this section for a second HEV with an APU that operates at EZEV levels.

3) The third scenario assumes that BOEVs will be used by all drivers on all daily travel that is within the battery range of the BOEV. These vehicles also are assumed to match ACVs in all elements of performance but not in range or refueling convenience. If the daily travel will exceed the battery range of the BOEV, an ACV will be used instead. In other words, the analysis assumes that the BOEV is "paired" with an ACV; the driver will choose the BOEV whenever possible, but the driver will choose the ACV for longer trips that exceed the range of the BOEV.

BOEVs and HEVs with battery ranges from 0 - 155 miles are modeled to show the impact of battery range capability.[6] Figure 11 illustrates the ability of both BOEVs and HEVs to "electrify miles," that is, to operate on batteries that were charged the night before with electricity from the electric utility.

Figure 11 also illustrates the surprising result that for any given battery range, HEVs could electrify, on average, more miles than BOEVs. The reason is because HEVs can be driven on all trips, and the initial miles every day will be powered by utility electricity.

Figure 11 - Personal Automobile Miles Electrified

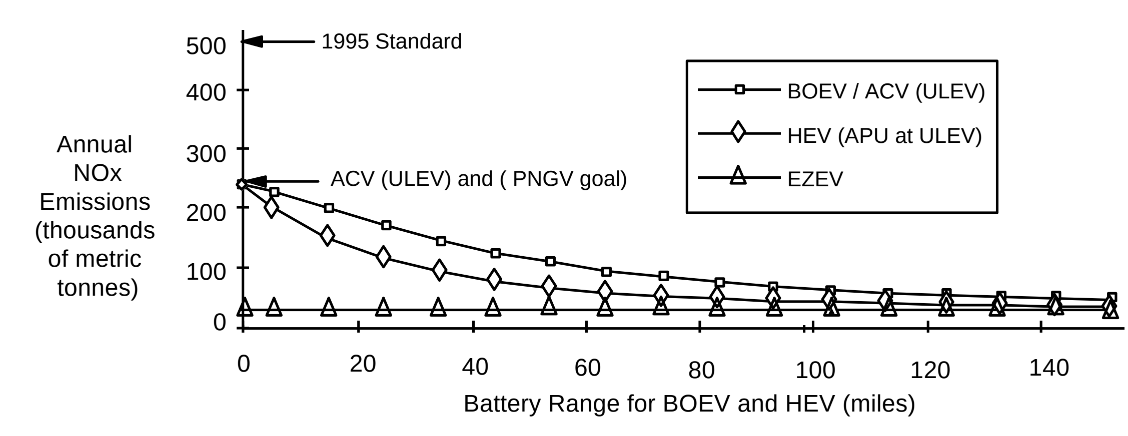


Source:1990 Nationwide Personal Transportation Survey (Ref. 6) and NEVCOR.

On the other hand, BOEVs can be driven only on trips within their battery range, and ACVs would be needed for the days with longer daily travel. (If there is the ability to recharge during the day, then the ability to electrify miles would be greater for both BOEVs and HEVs.)

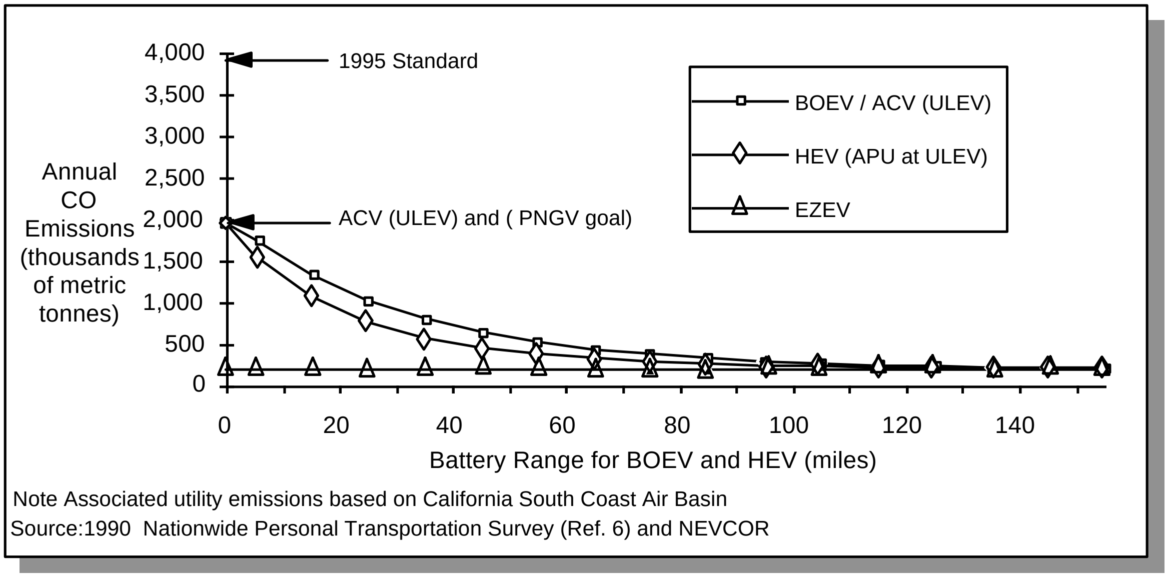
Figures 12, 13, and 14 illustrate the ability of BOEVs and HEVs to reduce emissions. The 1995 conventional vehicle baseline scenario, the PNGV goals[7] and the EZEV scenario are included as references (the PNGV goals are equal to the ACV (ULEV) level for NOx and CO). This analysis is intended as an assessment of the relative effects of each vehicle type, not as a prediction of future aggregate pollution or future impacts on air quality. See Appendix B for further details on the assumptions for the emission estimates.

Figure 12 - Annual Personal Automobile Exhaust and Associated Utility NOx Emissions



Note: Associated utility emissions based on California South Coast Air Basin.
Source:1990 Nationwide Personal Transportation Survey (Ref. 6) and NEVCOR

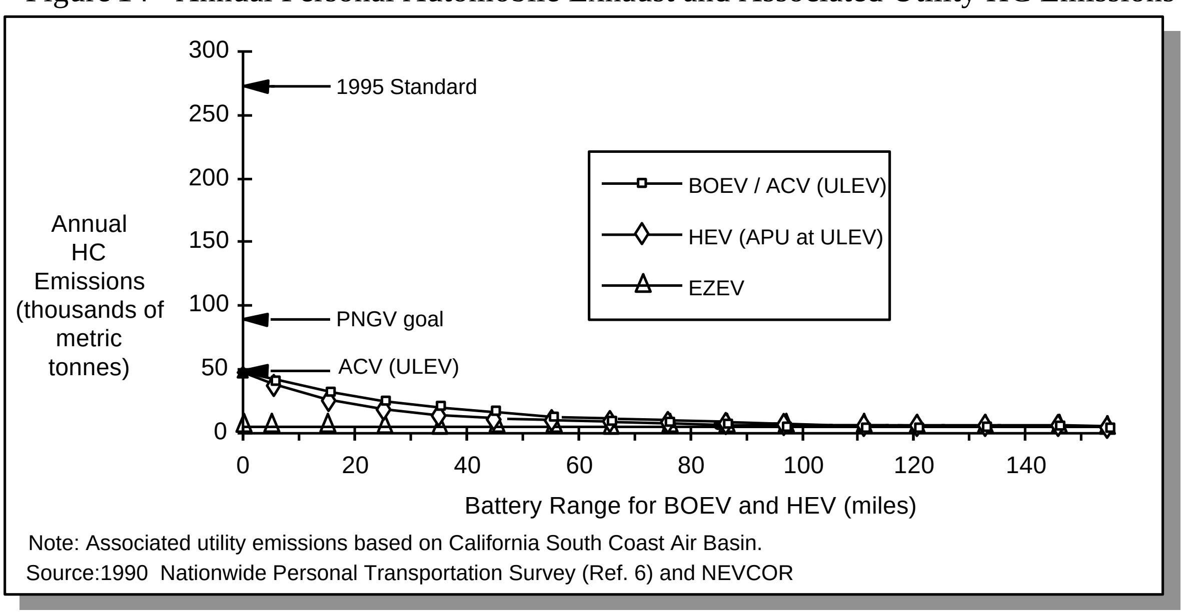
Figure 13 - Annual Personal Automobile Exhaust and Associated Utility CO Emissions



The principal conclusion from Figures 12-14 is that both BOEVs and HEVs are significantly superior to ACVs (and the PNGV goals) in terms of lowered emissions because both HEVs and BOEVs can travel on electricity from the utility.

Figures 12 - 14 also demonstrate the principle that for any battery range, HEVs create lower emissions than BOEVs because their battery range capability is used on all trips while the BOEVs are used only on those trips whose distance is within the battery range. Note that EZEV emissions are independent of battery range, that is, the HEV APU generates emissions at the same EZEV level as the power plants in California's South Coast Air Basin that provide electricity to the BOEV or HEV[8].

Figure 14 - Annual Personal Automobile Exhaust and Associated Utility HC Emissions



In addition to the above comparison of vehicles at maximum (100%) market share, it is useful to compare each vehicle technology at more "realistic" market shares. However, predicting market shares of new, unproved technologies in the marketplace is very difficult and beyond the scope of this report. Instead, the ARB ZEV market share mandate (that ZEVs must be 10% of new automobile offerings in 2003) will be used as a baseline in the following manner:

a) To meet the ARB ZEV mandate for 10% market share, the major auto manufacturers have stated that their BOEV must have a range of at least 100 miles. Thus, to compare BOEVs and HEVs at more realistic market shares, a 100-mile BOEV at 10% market share serves as the baseline scenario.

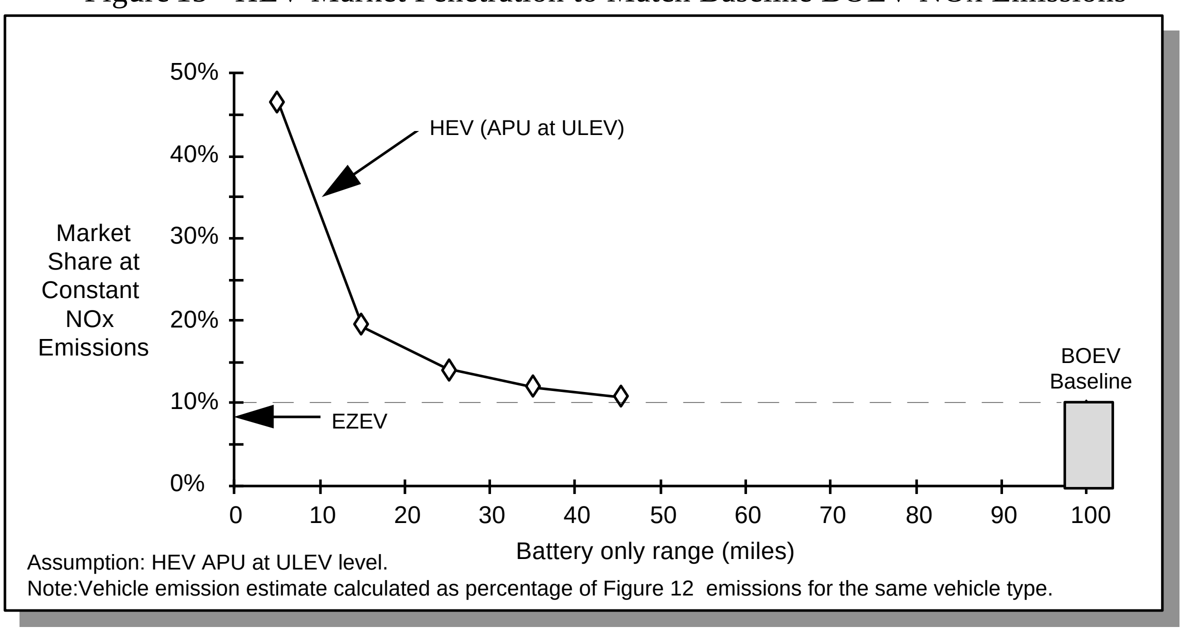
b) From the vehicle system emission estimates shown in Figure 12, the annual NOx emission reduction potential was calculated for a fleet of 100-mile BOEVs at 100% market share (with their accompanying ACVs for trips of greater than 100 miles) versus a fleet of 100% of today's conventional vehicles. This potential is 410,000 tonnes annually.

c) Next, 10% of this total emission reduction (41,000 tonnes) was used to estimate the emission reduction potential of 100-mile BOEVs at 10% market share.

d) Following the same methodology as in (b) and (c), the market share for the baseline HEV vehicle at various battery-only ranges was calculated such that the emission reduction potential of the particular HEV matches the emission reduction potential calculated in (c).

Figure 15 shows that a 15-mile battery-range HEV at 19% market share would provide the same emission reduction and electrify the same number of miles as the baseline 100-mile BOEV at 10% market share. In other words, two 15-mile HEVs would produce lower emissions and electrify more miles than one 100-mile BOEV. An EZEV HEV would need to capture only 8% market share to achieve the same emissions benefits as the baseline BOEV.

Figure 15 - HEV Market Penetration to Match Baseline BOEV NOx Emissions



V. Full-Cycle Emissions

As vehicle exhaust emissions are lowered to ULEV levels and below, other vehicle-related emissions and "upstream" emissions associated with fuel production and distribution begin to become critical. These other emissions are discussed in this section. While a full analysis of these emission sources is beyond the scope of this study, this section provides a guide to their relevance for HEVs.

Out-of-Cycle Emissions

There is increasing evidence that conventional automobiles produce emissions at far higher levels when in actual use than when tested under controlled federal test procedures. The Energy Foundation has reported results that indicate that actual "real-world emissions" are 5-10 times higher than those produced during federal test procedures (Ref. 11). Similar results have been reported by others (Refs. 12, 16,17,18).

These out-of-cycle emissions occur during hard acceleration, high-speeds, and hill climbing when there is a demand for increasing power from the engine. The baseline HEV, on the other hand, does not have these out-of-cycle emissions. The baseline HEV's APU operates in a steady-load mode that is independent of the rapidly varying demand for power to accelerate. Hence, these out-of-cycle emissions are altogether eliminated in the baseline HEV.

Malfunctioning Emission Control Systems (ECS)

A second cause of high in-use emissions are malfunctioning ECSs. Such malfunctions are more likely when the ECS is subjected to extreme operating conditions. Such extreme conditions occur in conventional vehicles under the same conditions as out-of-cycle emissions, that is, hard acceleration, high-speeds, and hill climbing.

The baseline HEV ECS is less prone to malfunctioning because the APU operates at a steady, predictable load. Also, the APU may not operate at all for many trips, depending on the battery-only range of the HEV. Thus, at the end of the vehicle's useful life (e.g. 100,000 miles), the APU and ECS may have only 50,000 miles of operation.

Vehicle Evaporative and Refueling Emissions

In gasoline-fueled vehicles, substantial emissions of volatile organic compounds (VOCs) can occur during refueling and during normal daily operations. To lower these emissions, Mitsubishi has reported a re-designed fuel system for its HEV that operates at a vacuum with respect to ambient conditions (Ref. 10). The VOCs are retained during refueling and during normal operation.

Also of significance is the possibility that regulatory emphasis in the future will shift from VOC control to NOx control (See Section IX and Ref. 15). Such a shift could alter the priorities regarding evaporative emissions.

Upstream Emissions

According to the Union of Concerned Scientists (Ref. 12), upstream emissions of NOx are due mostly to refineries. In the ARB's approach to full-cycle emissions control, a substantial effort is made to allocate upstream NOx (and other upstream emissions) to each vehicle on a per mile basis. However, critics of this methodology argue that the emissions of a refinery are better considered as a stationary source. For example, they point out that a portion of the gasoline from the refineries in the South Coast Air Basin (SCAB) is now shipped out of the region. They argue that as less gasoline is used in the SCAB (e.g. because of increasing numbers of HEVs and BOEVs driving on utility electricity), more gasoline will be shipped out of the SCAB. The refineries are likely to continue to refine the same amount of gasoline and produce the same level of emissions. Thus, an attempt to control upstream in-basin NOx emissions with regulations on vehicles would not result in reduced in-basin NOx emissions.

In any event, when full-cycle emissions are tied to each vehicle on a per-mile basis, then HEVs can be considered equivalent to BOEVs. That is, if BOEVs and HEVs travel, on average, the same annual miles on electricity, then they would displace equal amounts of fuel and the associated per-mile upstream NOx emissions from the oil refineries. The next section presents an analysis of HEV and BOEV use of electricity and fuels as battery range varies.

VI. Fuel and Electricity Use

The U.S. economy is highly dependent on petroleum imports due in large part to the consumption of gasoline by automobiles. This dependence on a foreign energy source creates significant economic costs and security risks. Thus, it is important to understand the ability of any new vehicle technology to minimize the use of imported energy.

HEVs can reduce gasoline use in two ways. First, HEVs can displace gasoline by using utility electricity to charge the HEV's battery pack. A shift from gasoline to utility electricity is an effective way to reduce petroleum imports and improve energy security. Most of America's utility electricity is generated from domestic, non-petroleum feed stock. When utility electricity is generated from imported natural gas, Canada and Mexico are the main sources of this fuel. These countries present much lower security risks and costs than overseas regions that supply a large part of America's petroleum imports.

Second, HEVs can be designed to be more fuel efficient. HEVs with an efficient electric-drive system, optimally sized APU, on-board energy storage, regenerative braking and an effective control strategy can be much more fuel-efficient than ICE-powered vehicles. The DOE's HEV Propulsion Project has a near-term 55-mi/gal (2X) target that reflects this opportunity (Ref. 13).

Vehicle fuel efficiency is also a key driver of profitability for American auto manufacturers. At present, American automobile manufactures are regulated to ensure that the average fuel efficiency of their automobiles sold each year is at least 27.5 mi/gal. American auto manufacturers sell a wide range of automobiles with significantly different fuel efficiencies. It is well understood that the American auto manufacturers earn much higher margins on their larger vehicles that have correspondingly lower fuel efficiencies. Thus, any new vehicle technology that can deliver increased fuel efficiency in the large, more profitable, vehicles could offer American auto manufacturers the opportunity to significantly increase profitability by shifting their vehicle mix to the larger more profitable vehicles while still meeting CAFE standards.

It is interesting to observe that HEVs with relatively short battery range can be as effective in reducing gasoline use as dramatic increases in vehicle fuel efficiency (see Figure 16). Three potential development programs to reach the PNGV's 3X target illustrate this comparison:

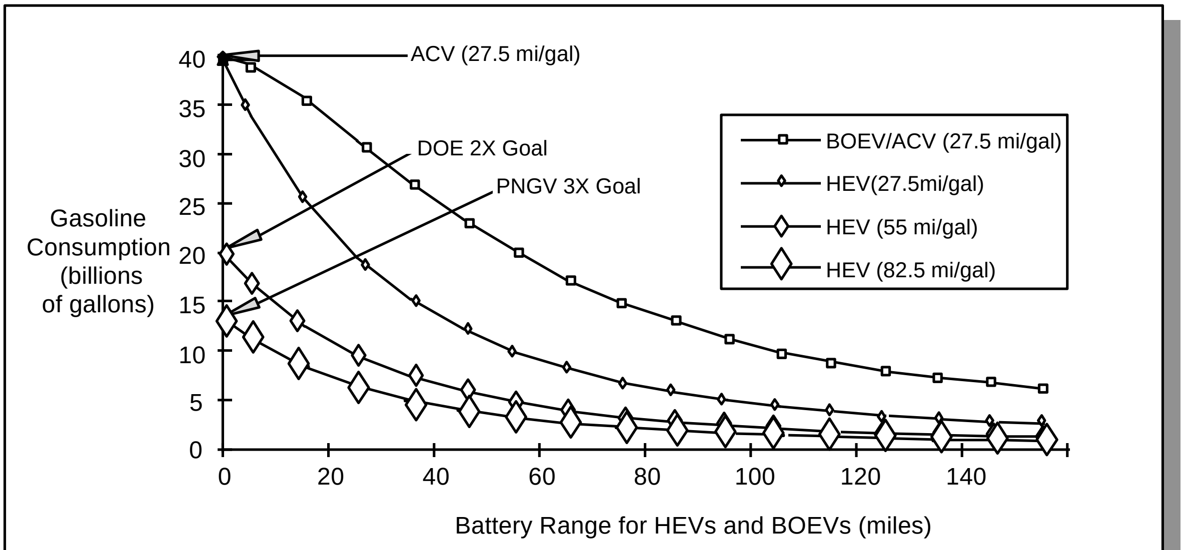
1) The PNGV path is to begin with the DOE's 2X HEV Propulsion Project and then couple that technology with an advanced lightweight aerodynamic vehicle to improve fuel economy to 3X. In such a system, battery range would be minimized to reduce weight (Ref. 13). Fuel use would be reduced to 13 billion gallons, roughly one-third of today's 40 billion gallons (see Figure 16).

2) An alternative program to reach the target would be to couple the DOE 2X HEV propulsion system with a 15-mile range battery pack system in a conventional vehicle. Battery technology exists today that can cost-effectively provide this range. Such a vehicle would displace an equivalent amount of gasoline (see Figure 16) and could be an early-to-market low-cost alternative.

3) A third option would be an HEV with a 40-mile battery that has a fuel efficiency when using the APU of only 27.5 mi/gal (see Figure 16).

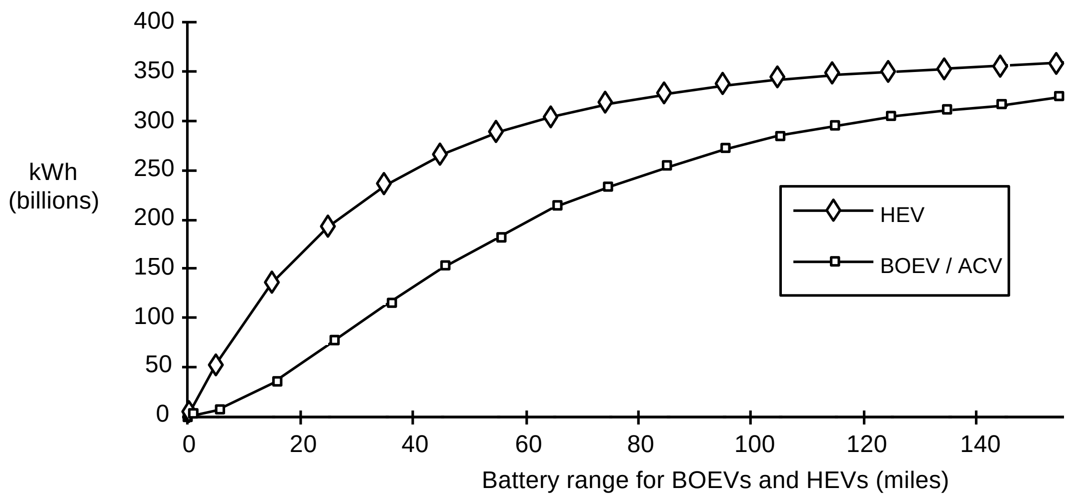
As the battery range of BOEVs and HEVs rise and gasoline use declines, electricity use increases (see Figure 17). However, for any given battery range, HEVs would travel, on average, more miles on utility electricity than BOEVs because HEVs could be used on all trips, and the initial miles will be on electricity stored from the night before.[9]

Figure 16 - Annual Personal Automobile Gasoline Use



Source: 1990 Nationwide Personal Transportation Survey (Ref. 6) and NEVCOR

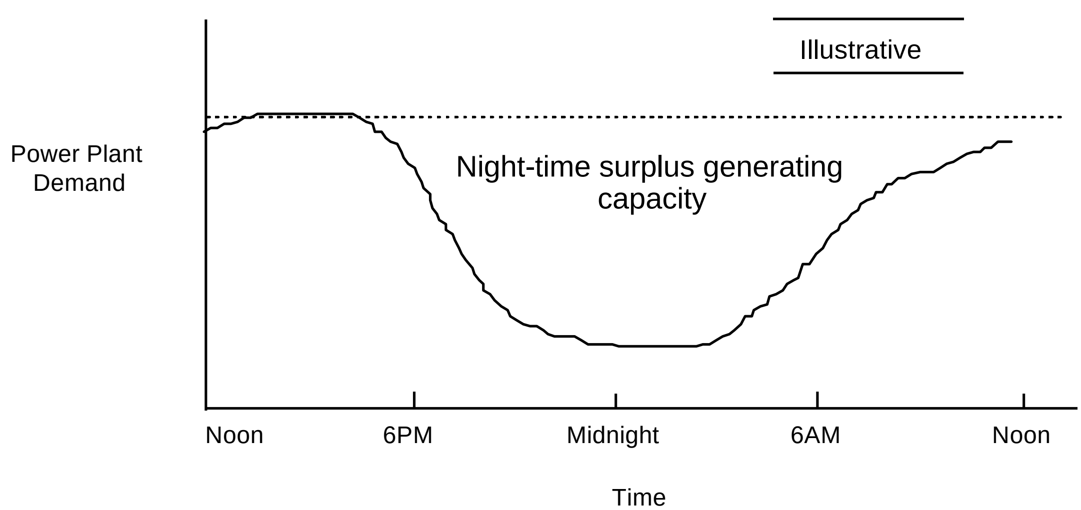
Figure 17 - Estimated Annual Electricity Use in Personal Automobiles



Note: 352 Wh/mile assumed for both BOEV and HEV.
Source: 1990 Nationwide Personal Transportation Survey. (Ref. 6)

It is expected that HEV owners will be motivated to use night-time utility electricity to recharge their batteries for two reasons. First, it will be more convenient for many owners to recharge their vehicle at night when the vehicle is parked in the driveway or garage than to stop at a gasoline station and refuel. A strong case has been made that BOEVs will be attractive for this very reason (see Ref. 19). Second, a study by Volvo argues that operating an HEV on utility electricity will be less costly than operating the same vehicle from fuels in the APU (Ref. 14).

Figure 18 - Power Plant Demand Profile



In fact, since utilities have a drop in demand at night (see Figure 18), they are motivated to offer reduced night-time rates to encourage night-time use. By using the excess capacity at night, utilities will be able to run more efficiently which could lead to a reduction in the average cost of electricity. However, the electricity use shown in Figure 17 should be considered as the upper limit. For example, HEV (and BOEV) owners may forget to plug in to recharge. Even if they do plug in, a BOEV owner may chose to use an ACV because of uncertainty regarding that day's travel plans. Also, it is a fact that HEV owners are not required to plug in, since the HEV APU permits operating by refueling with gasoline just like an ordinary vehicle. For these reasons, the maximum possible electricity use for both HEVs and BOEVs shown in Figure 17 may need to be discounted by some factor to recognize "reasonably expected" consumer behavior regarding plugging in for HEV and BOEV drivers as well as the amount of "battery-range-reserve" required by BOEV drivers.

VII. Other HEV Control Strategies

HEVs can be designed in a variety of ways to accomplish different missions or to achieve different objectives. This report focuses on HEV designs targeted at personal automobile use with the dual objectives of reducing emissions and reducing gasoline use. The continuous mode HEV design has been used as a baseline to assess the benefits of HEVs broadly. This section looks at four other HEV control strategies to assess how they compare with the baseline design in terms of fuel use and emissions reduction. The detailed analysis is outlined in Appendix B. The following five designs were assessed:

1) Charge-sustaining continuous series HEV (baseline).
2) Charge-sustaining Mitsubishi series HEV.[10]
3) Charge-sustaining thermostat series HEV.
4) Charge-depleting series HEV.
5) Charge-depleting parallel HEV.

The continuous, Mitsubishi and thermostat strategies are all charge-sustaining. This means that the vehicle's APU is sized large enough to allow the vehicle to travel "unlimited distances" (i.e. between gasoline tank fill-ups) at acceptable performance levels (i.e. acceleration, top speed, accessory loads, hill climbing).

The charge-depleting series HEV has a smaller APU that cannot meet the average energy requirements of the automobile. Thus, the state-of-charge (SOC) of the battery pack continually declines, even with the APU operating, until the vehicle is forced to rely solely on the APU. At this point, the vehicle's performance is significantly diminished as the APU cannot meet the standard acceleration, speed and accessory load requirements. Thus, the vehicle operates in a "limp-home" mode where in it's top speed and acceleration capability is significantly lower than when in "standard" mode. The charge-depleting series HEV is a limited-range vehicle that must be analyzed as paired with a conventional vehicle, similar to the analysis of the BOEV/ACV pair.

Both the continuous and charge-depleting series HEVs continuously operate the APU throughout the trip once a predetermined battery SOC is reached. The continuous HEV operates its APU at a constant level to maintain SOC. The operation of the Mitsubishi HEV is similar to the continuous model except that the Mitsubishi HEV shuts off the APU each time the vehicle comes to a stop.[11]

The thermostat HEV operates its APU at a higher level that provides enough energy not only to meet the vehicle's operating requirements but also enough to recharge the battery. Thus, the thermostat APU will cycle on to recharge the battery until a predetermined high SOC is reached and then it will shut off.

In the charge-depleting parallel HEV, the electric motor provides all torque requirements if the vehicle's speed is below a threshold level. The threshold for this simulation was approximately 22 mi/h. Above this threshold, the APU engine provides all torque required; the electric motor is used above 22 mi/h only to recapture braking energy and to provide any peak accelerating power that the APU cannot provide. The parallel mode is charge depleting, and as the battery SOC declines, the APU is used at lower and lower vehicle speeds.

The HEV computer simulation model ADVISOR, developed by NREL, was used to compare control strategies. The same vehicle, APU, battery pack and electric motor were modeled for all strategies. The control strategies were compared based on the FTP driving cycle. With the APU providing all the necessary energy, the emissions and fuel use produced by each vehicle over the FTP driving cycle were simulated (See Appendix B for more details).

The results of the simulation analysis are outlined in Figure 19. The fuel use and emissions are reported as scalar factors relative to the results of the baseline continuous HEV. Reasons for differences in the results from the baseline HEV are discussed below.

Thermostat

The operating point for the thermostat mode was chosen to be the optimum point for the control of NOx, HC and CO with satisfactory fuel-efficiency.

Figure 19 - HEV Simulations - Emissions and Fuel Use Results

	Fuel Use	HC Emissions	CO Emissions	NOx Emissions
Continuous (Baseline)	1.00	1.00	1.00	1.00
Mitsubishi	0.91	1.50	2.26	0.94
Thermostat	0.86	0.75	2.13	0.08
Charge Depleting (and ACV companion)	NA	0.80	1.19	0.84
Charge-Depleting Parallel	0.71	8.79	253.00	0.19

When compared to the continuous mode control strategy, the emissions in the thermostat mode are dramatically lower for NOx, and the fuel economy is higher (see Figure 19). HC is lower and CO is higher but these differences are not as significant. This result illustrates the benefit of operating an engine at its ideal operating point so that emissions can be reduced to their lowest levels. At this ideal operating point, engine fuel efficiency can be maintained at near maximum levels. In the thermostat mode, the increased charge/discharge losses in the energy storage system are more than off-set by the improved engine efficiency.

Mitsubishi

Fuel economy in this mode is somewhat better than for the continuous mode but still not as good as with the thermostat mode. Emissions are roughly comparable to the continuous mode.

Parallel

The key benefit of the parallel mode is that the APU operates only at vehicle speeds above the threshold; thus, operation of the engine at low speeds and low torque can be avoided.

As can be seen in Figure 19, HC and CO emissions are much higher than for any of the series HEV modes. Fuel efficiency is the highest, reflecting the fact that the inefficient low-speed and idling ICE operating modes have been displaced by the electric motor. NOx is lower than in the continuous mode but not as low as in the thermostat mode. Because this is a charge-depleting mode, fuel economy and emissions will be somewhat poorer when a correction factor is added to compensate for the net reduction in SOC.

Charge-depleting Series

Due to its limited range, the charge-depleting HEV is modeled assuming that an ACV would be used for the longer trips. It is assumed that the driver would not plan to operate the vehicle in the "limp-home" mode and instead would use an ACV on days when the expected travel distance was beyond the range of the charge-depleting HEV. The charge-depleting HEV was modeled to have a battery-only range of 25 miles and a total extended range with the APU of 65 miles. This charge-depleting HEV with a companion ACV is then compared with a 25-mile battery-range continuous mode HEV to generate the scalar factors shown in Figure 19. The comparison is done in the same manner as was done with the BOEV as is outlined in this report.

As would be expected, emissions are comparable to the emissions in the continuous mode control strategy. However, the vehicle would have a limited range, and the vehicle would not be suitable for more high-power sustained travel, such as mountain driving.

Model Limitations

An important limitation of the model is that the enrichment of air-fuel mixture that occurs during acceleration is not modeled. This enrichment appears to be a significant cause for underestimation of "real-world" emissions by the standard FTP protocol (Ref. 11, 12, 16-18). This model limitation would result in an underestimation of emissions in the parallel simulation. The Mitsubishi mode also undergoes a change in engine torque each time the vehicle comes to a stop. However, it is likely that the increasing torque can be programmed in such a way that enrichment is not necessary. Given this assumption, the model results for the Mitsubishi (and the other series HEV modes) are representative for comparison among control strategies.

Conclusions

With the specified engine and catalytic converter, NOx can be reduced in a series HEV to 1/10 ULEV (that is, to 0.02 g/mile) over an operating range of 10 kW to 20 kW (see Appendix B and especially Figure B8). This is equal to the new EZEV level proposed by the California Air Resources Board (see Figure 1). However, HC would be about .3-.4 g/kWh (.1 g/mi) over most of this range, dropping to about 0.05 g/mi only when power levels were near 20 kW.[12] Fuel efficiency of the engine over this 10-20 kW range would be near maximum.

The ability to reach these low levels of NOx may be especially significant because of the increasing emphasis that may be placed upon NOx control in the future.[13]

It also should be understood that other engines and other ECSs (emissions control systems) could be modeled to assess their suitability for each of these control strategies. For example, the continuous mode could result in the same low emissions as the thermostat mode if the APU engine were down-sized so that the necessary power was provided at the engine's ideal operating point. Such a vehicle could be suitable for applications such as metropolitan taxis wherein the vehicles are not required to have sustained high-power capability (e.g., for mountain grades). Such vehicles are in day-long stop-and-go urban and suburban traffic where average power levels are relatively low, opportunities for regenerative braking are high and daily travel distances could be significant.

Note that Mitsubishi Motors has reported actual emissions with their test vehicle (using their engine and control strategy and ECS) close to or at EZEV levels for all three target pollutants (Ref. 10). NEVCOR, also, has achieved EZEV emissions levels for NOx with its XA-100 prototype series HEV.[14] Once NOx has been reduced to EZEV levels, it is also theoretically possible to add an oxidizing ECS to further lower HC and CO emissions.

VIII. Policy Implications

Properly-designed HEVs can offer substantial social benefits in terms of reduced emissions and improved fuel efficiency. By plugging into the electric utility, HEVs, like BOEVs, can further reduce fuel use and emissions by displacing fuels with utility electricity. In addition, HEVs offer the performance, range and "full-tank" feeling of security that drivers now have in conventional vehicles, while the relatively small, low-cost battery packs of an HEV may make HEVs more affordable than their BOEV counterparts.

Hence, HEVs may broaden significantly the market beyond the market that exists for BOEVs alone. This larger market would enable larger economies of scale, higher production levels and lower per-vehicle costs for both HEVs and BOEVs. The results could be a greater market penetration with correspondingly greater benefits (e.g., reduced emissions, reduced fuel use and increased use of electricity) than would be possible with BOEVs alone. (See Section IX for proposed studies regarding HEV costs.)

For these reasons, regulations, R & D initiatives and financial incentives should be consistent with these benefits in order that a "level-playing field" be created for all alternative vehicle-fuel systems. In so doing, regulators can assist the introduction of HEVs by recognizing their social benefits in vehicle regulations.

The focus of this section is the California zero-emissions vehicle (ZEV) mandate. This section does not address the timing or quotas of the ZEV mandate but instead focuses on the treatment of HEVs under the ZEV regulations.

The ARB staff has proposed to qualify HEVs for ZEV credit under two methods (Ref. 5). First, any vehicle whose full-cycle emissions (exhaust, evaporative, upstream) are equal to or less than the South Coast Air Basin (SCAB) power plant emissions associated with a BOEV will qualify as a ZEV. These vehicles are called equivalent zero-emission vehicles or EZEVs. It is likely that HEVs with their APUs fine-tuned to minimize emissions will be among the first vehicle types to meet this standard.

The second way in which HEVs can qualify for ZEV credit is with their ability to electrify miles. Based on NPTS data and a vehicle's "battery" range, an HEV is given a fraction of ZEV credit corresponding to the percentage of miles it would electrify. The full-cycle emissions from these HEVs when running their APUs must be equal to or less than the ULEV standard[15].

These proposed HEV regulations attempt to recognize the benefits of HEVs, but they still do not adequately account for the social benefits of HEVs. While BOEVs receive full ZEV credit regardless of their battery range and corresponding ability to electrify miles, HEVs would receive only partial ZEV credit. Yet, for any given battery range, HEVs would electrify on average, more miles than a BOEV.

To resolve this inequity and to assess BOEVs and HEVs on a level playing-field, the following principles derive from the new EZEV category and should be considered as guidelines when drafting regulations and interpreting the ZEV mandate:

1) EZEVs could be considered the "baseline" ZEV with which all other technologies are compared. If EZEVs (like ACVs) are not range-limited, they can be used on all trips, regardless of trip length or total daily miles traveled. Thus, in terms of emission reductions, these EZEVs are equivalent to "electrifying" 100% of the miles driven by the driver. (Note that, in theory, a vehicle could achieve emissions that are even lower than those associated with SCAB power plants. Were such vehicles developed, then a new, even more stringent emissions level could be created to reward these vehicles.)

2) "Percentage of miles electrified" is useful in assessing all technologies under the ZEV mandate. Thus, the amount of ZEV credit granted to BOEVs and HEVs would be in proportion to the "percentage of miles electrified." Ideally, HEVs and BOEVs should be given ZEV credit based on their ability to reduce emissions as compared to an EZEV. However, granting ZEV credit based on miles electrified greatly simplifies the comparison and is a fairly accurate proxy for emissions reduced. This principle can

serve as the baseline from which to apply ZEV credit multipliers for the early introduction of advanced technology.

Figure 20 - ZEV Credits (ARB Proposals and Credits based on Miles Electrified)

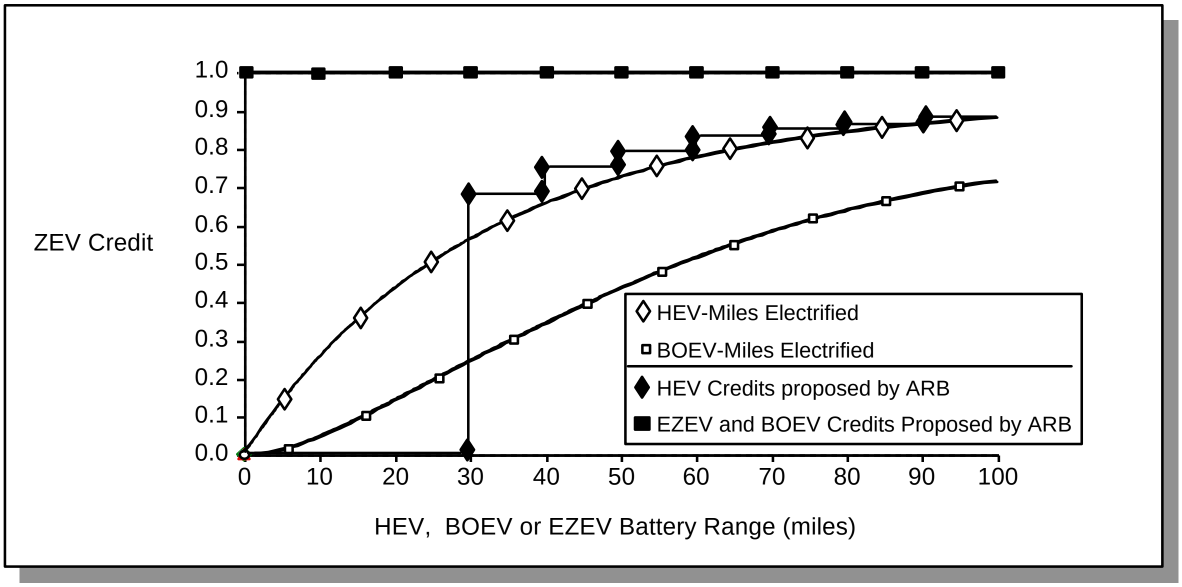


Figure 20 displays the ZEV credits offered under the ARB proposed amendments for HEVs, BOEVs and EZEVs. Note that BOEVs (and EZEVs) receive full credit regardless of battery range. This makes sense for EZEVs whose full-cycle emissions when using their APU are equal to or less than the electric power plant emissions for BOEVs. However, it would appear reasonable to offer more credit to a 100-mile BOEV than a 50-mile BOEV.

Figure 20 also displays the ZEV credits that would be offered based upon the two principles discussed earlier. HEVs and BOEVs would be offered ZEV credit based on miles electrified. Under these two principles, an EZEV would receive a ZEV credit of 1.0, a BOEV with a battery range of 100-miles would receive a ZEV credit of 0.71, and an HEV with a 15-mile battery range would receive a ZEV credit of 0.36.

In conclusion, properly-designed HEVs could offer the consumer in the near term an affordable and appealing alternative to conventional vehicles while achieving the national priorities of reduced fuel use and reduced emissions. Were HEVs to become competitive in cost with ACVs and were their performance to compare with or exceed that of ACVs, then HEVs could very well dominate the automotive market.

However, as a new technology, HEVs face formidable institutional barriers. Investment is likely to languish as long as regulatory policies fail to reward the benefits of HEVs in an equitable manner as compared with other technologies.

To paraphrase Eberhardt Rechtin, Assistant Laboratory Director of the Jet Propulsion Laboratory, almost 30 years ago in his seminal article on system engineering, if we legislate the wrong priorities, we will surely end up with the wrong outcome.

> *The establishment of ordered, quantitative objectives is a difficult, but vital task. Establishing the right objectives is so important that a significant fraction of the total time needed to solve the problem must be spent on this step.* ***The wrong objectives lead to the wrong system.*** *[Emphasis in the original.] (Ref. 21)*

IX. Further Study

The analysis presented in this paper broadly outlines the major benefits of HEVs and the resulting policy implications. Further study in some key areas is critical to more accurately identify the potential of HEVs. NEVCOR has developed research plans in these areas:

1) Market penetration: Realistic market penetration rates for HEVs and other alternative vehicle technologies should be modeled to better understand the total emission reductions potential of each technology. Preliminary analyses show that limited-range BOEVs would have niche market appeal (e.g., as second cars in 2-car households) and are thus more limited in their marketability than HEVs that appeal to the broad market (Ref. 19). Further analysis is also required to determine if BOEVs will replace or just complement conventional vehicles. This issue is particularly critical in understanding the impact of BOEVs on evaporative emissions from their companion ACVs.

2) Regional analysis: Regional driving behavior and utility power plant emissions associated with electric vehicles directly impact the relative emission benefits of various technologies in each region. Southern California has one of the cleanest utility systems in the U.S. and thus their "EZEV" standard is likely to be much cleaner than an EZEV standard in a region with predominately "coal-fired" power plants. Trip statistics also could vary significantly by region which may alter the "miles-electrified" calculation for ZEV credit.

3) Other vehicle types: HEV technology is readily applicable to other vehicle types, such as sport utility vehicles, pick-up trucks, heavy-duty trucks, buses etc. The relative benefits of HEVs (versus other technologies) may be even larger for these vehicle types than the benefits identified in this paper for personal automobiles.

4) Full-cycle emissions: Once vehicle exhaust emissions are reduced to ULEV and sub-ULEV levels, evaporative, upstream and distribution emissions become much more significant. In fact, in some studies the non-exhaust emissions dominate the exhaust emissions (Ref. 20). Thus, it becomes critical to fully understand the relationship between vehicle usage and total emissions to best assess how to reduce emissions. See also the issue of NOx versus VOC control discussed next.

5) NOx vs. VOC[16] control: Recent research indicates that regional ozone reductions may be possible only with NOx control because anthropogenic inventories of VOCs (including HC from autos) have been significantly underestimated and background biogenic VOC inventories are so large. "*In the presence of anthropogenic NOx..., these background biogenic VOCs can contribute to summertime ozone concentrations exceeding the NAAQS concentration of 120ppb [even if all anthropogenic VOC emissions were eliminated].*" (Ref. 15). Analysis is needed to determine the potential of new vehicle technologies (BOEVs, HEVs, LEVs, ULEVs...) to achieve dramatic reductions in NOx.

6) Electric utility impacts: HEVs and BOEVs are a welcome nighttime utility load, utilizing existing 110v (or 220v) circuits, tapping idle generating capacity and improving utility efficiency. However, if HEVs are designed to use the APU all the time and if they are not equipped with the ability to plug in and recharge, these benefits to both consumers and utilities would be lost. For these reasons, the utilities have a great deal to gain, or lose,

regarding the direction HEV designs take. The potential impacts of HEVs on the utilities needs to be explored, and the proper course of action for the utilities needs to be developed.

7) Petroleum industry impacts: At first glance, HEVs would appear to result in a net loss of sales for the petroleum industry. By displacing fuel with electricity, the petroleum industry would see a gradual decline in gasoline sales. Yet, the petroleum industry also has a goal of a favorable public image, as evidenced by the numerous television ads depicting oil company concerns for clean air. Were the oil companies to lose that portion of the transportation market representing the shortest trips, the resulting emission reduction might far outweigh the loss of market share. A 1% reduction in fuel use (from the shortest trips) could result in a 10% reduction of emissions. Further emission reductions could occur when fuels were used in HEVs with APUs operating at EZEV levels rather than ACVs operating at ULEV levels (or worse). Perhaps, in some creative way, some sort of credit could be given to the oil industry for assisting in the introduction of HEVs and helping to achieve the environmental objective of reduced emissions.

8) HEV cost: The capital and operating costs of HEVs with inexpensive battery packs need to be compared with similar costs for advanced conventional vehicles. Conceptually, HEVs built on a conventional platform with a small light-weight battery pack and small APU could be cost competitive with conventional vehicles when both are in mass production. Further analysis of “mass-production” costs is necessary to better understand any cost differential that might persist between ACVs and HEVs.

Footnotes

[1] Average reduction in NOx and VOC from 1965 typical pre-control car to 1993 standards as measured by official federal test procedures. See Reference 2.

[2] South Coast (Los Angeles), Sacramento Metropolitan Area (encompassing five local air control districts), San Diego, San Joaquin Valley, the Southeast Desert, and Ventura. See Reference 3.

[3] This report focuses on the emissions benefits and regulatory treatment of BOEVs and HEVs. It does not address the timing and numerical quotas.

[4] The EZEV is a vehicle standard proposed by the ARB that certifies the vehicle to emissions levels that are considered equivalent to the associated "in basin" utility emissions in charging an electric vehicle in California's South Coast Air Basin (SCAB).

[5] The Nationwide Personal Transportation Survey is conducted by the Department of Transportation. In 1990, over 48,000 people were surveyed with questions concerning their daily transportation activities. See Reference 6.

[6] There is wide-spread agreement that BOEVs must have at least a 100-mile battery range to appeal to more than just a niche market (see Ref. 7). HEVs, because of their unlimited range capability, could appeal more broadly and could have much shorter battery ranges that were tailored to the typical daily travel of the owner. For this reason, the results of this study are presented as a function of battery ranges from 0-155 miles to permit a broad comparison of emissions and energy use for different battery-only ranges.

[7] PNGV emission goals are stated as National Tier II vehicle emission levels with no recognition or requirement of battery-only range. (HC .125 g/mi., NOx .2 g/mi., CO 1.7 g/mi.)

[8] Note that in other regions of the U.S., such as the East and Midwest, where utility power plants are not as clean as those in Southern California, an EZEV would actually result in lower emissions than a BOEV. This point is addressed again in Section IX - Further Study.

[9] For this analysis, it was assumed that the BOEV and HEV energy efficiency were the same (352 Wh/mi).

[10] The Mitsubishi operating mode modeled in this study is a simplified simulation based upon Reference 10; it is not meant to be an exact replication of the Mitsubishi program.

[11] Ibid.

[12] HC (and CO) could be further reduced, in theory, with the introduction of an additional oxidizing emissions control system.

[13] See section IX. See also Reference 15.

[14] These test vehicles need further work to demonstrate their performance as marketable vehicles.

[15] While HEV APUs must meet ULEV levels for full-cycle emissions (exhaust, evaporative and upstream emissions), ACVs are not subjected to the full-cycle requirement. To meet ULEV standards, ACVs need only achieve ULEV levels at the exhaust. This is one of several inconsistencies that are part of the current regulations. For example, by one ARB estimate (Ref. 20) upstream NMOG emissions alone exceed the 0.04g/mi ULEV standard. In other words, an HEV with zero exhaust emissions and zero evaporative emissions still would fail to achieve any ZEV credit. However, BOEVs would receive full ZEV credit, even though their drivers would still need a conventional vehicle (with its evaporative and upstream emissions) for long trips.

[16] VOC: Volatile Organic Compounds, sometimes referred to as ROG (Reactive Organic Gases).

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Appendix A: Glossary

ACV	Advanced Conventional Vehicle powered by an ICE
APU	Auxiliary Power Unit (e.g. an engine-alternator)
ARB	Air Resources Board of California
BOEV	Battery-only Electric Vehicle
CAFE	Corporate Average Fuel Economy
CO	Carbon Monoxide
CO2	Carbon Dioxide
ECS	Emission Control System
EV	Electric Vehicle
EZEV	Equivalent zero-emissions vehicle (new emissions category proposed by the ARB with 1/10 the emissions of ULEVs)
g/kWh	Gram per kilowatt hour
HC	Hydrocarbons
HEV	Hybrid-Electric Vehicle
ICE	Internal Combustion Engine
mi/gal	Miles per Gallon (measure of vehicle fuel use)
mi/h	Miles per Hour (measure of vehicle speed)
Nm	Newton-meter (measure of torque)
NMOG	Non-methane Organic Gases
NOx	Nitrogen Oxides
PNGV	Partnership for New Generation Vehicles (Joint venture between the U.S. Government and General Motors, Ford and Chrysler.)
rad/s	Radians per second (measure of engine speed)
ROG	Reactive Organic Gases
tonne	metric ton (1000 kilograms)
SOC	State-of-Charge
ULEV	Ultra-Low Emission Vehicle (ARB's most stringent ACV emission standard now on the books)
VOC	Volatile Organic Compounds; sometimes called Reactive Organic Gases (ROGs)
ZEV	Zero-Emissions Vehicle

Appendix B: Methodology

1. Exhaust Emissions Simulations

NEVCOR's initial automotive exhaust emission analysis (see Ref. 9 and Figure B1) was undertaken with the simplifying assumption that vehicles emit at a constant, unchanging ULEV level for all miles traveled. However, in actual operation, motor vehicles have much higher emissions at cold start-up than during hot running operation (see Figure 3). Therefore, to more accurately assess the emissions impact of various vehicle technologies, the effect of frequent starts and high start-up emissions must be simulated. To do so, the NEVCOR conducted the following analysis

A) Model ULEV Emissions

The first step is to model the emissions rates of a "series" hybrid-electric vehicle that meets ULEV standards. The vehicle control strategy assumes that the electric drive motor provides 100% of the torque required to drive the vehicle. The engine/alternator (auxiliary power unit (APU)) is assumed to operate at a steady speed and load, maintaining the battery state-of-charge (SOC), on average, at a constant level. The APU operates so that battery SOC at the end of the test is equal to the SOC at the beginning of the test.

A series of simulations, using an early version of ADVISOR, the MATLAB/Simulink hybrid vehicle simulator developed by the National Renewable Energy Laboratories, was run to develop a model of an HEV that would certify to ULEV levels on a standard FTP FUDS test. A Geo Metro engine simulation was used as the basis for the APU model. This simulation calculates tailpipe emissions according to the following equation:

$$\text{Emissions (g/s)} = C * (P_{eng}) * (\text{hotgkWh}) * (f(\text{TEC})) * (1 - \text{Cateff}) \quad (1)$$

where:

C = constant
P_{eng} = engine power
hotgkWh = g/kWh of engine-out pollutants (HC, CO, or NOx) under steady-state running conditions
f(TEC) = a multiplier linked to the temperature of the engine coolant
Cateff = catalytic converter efficiency as a function of catalyst temperature

Using the first three terms, Equation (1) calculates a baseline emission level (for a hot engine running at steady-state) that is proportional to engine power. The emissions are then increased with the parameter f(TEC) for engines of varying temperature between ambient (20 _C) and full-temperature (TEC=95 _C). The resulting emissions are then reduced by the efficiency of the catalyst, Cateff. Equation (1) is solved second-by-second to yield emissions levels from low-power cold-start to high-power at hot running temperature. These rates are then integrated over a full FTP cycle and weighted according to FTP standard weightings for Bags 1, 2, and 3.

The GEO Metro APU emissions were scaled in the following manner. First, the TEC and catalytic converter efficiency parameters were left unchanged. Then the model was run with output power (P_{eng}) at 6.6 kW, the average power required of the engine for this vehicle on an FTP test. At this 6.6 kW power level, the GEO Metro APU model produced .23 g/mi HC, 1.97 g/mi CO, and .31 g/mi NOx during the FUDS simulation. Then, the parameter "hotgkWh" was scaled to force these tailpipe emissions down to ULEV levels for each pollutant (see Table B1 below). Because this parameter has a linear effect upon tailpipe emissions, the "hotgkWh" values were easily computed as fractions of the original NREL values. For example, the proper input value for "hotgkWh" of HC is:

$$hotgkWh_{ULEV} = (.04/.23) * hotgkWh_{NREL} \qquad (2)$$

These changes resulted in a simulated HEV that 1) was SOC corrected (i.e. the SOC at the end of the FTP was equal to the SOC of the beginning of the FTP) and 2) met ULEV standards for all three primary pollutants.

Table B1: ULEV Standards

HC	CO	NOx
0.04 g/mi	1.7 g/mi	0.2 g/mi

B) Model Engine Cool-Down Effect

The second step was to determine the effect of cool-down times on engine start-up emissions. A second series of simulations was run using the ULEV vehicle from Step 1 to examine the impact of various length "cold soaks" on engine start-up emissions. Figure B2 shows the variation of start-up emissions for 13 different cool-down times. For all curves, the engine start occurs at t=0. The curve marked 1 indicates engine start-up after a 1-hour cool-down time, the curve marked 2 indicates engine start-up after a 2-hour cool-down time, and so on. The "Ambient" curve indicates emissions levels for a vehicle that starts while at ambient temperature (20 C). As expected, an engine which has had little time to cool off produces less start-up emissions than one that has cooled down for several hours.

C) Determine Distribution of Engine Cool-Downs

The third step was to examine the NPTS data to understand the distribution of engine starts as a function of cool-down time. This distribution is shown in Figure 4.

To simplify calculations, it was determined that the trip data would be aggregated into 3 groups: hot, warm, and cold starts. Definitions for the three groups are as follows:

a) Hot Starts: Trips which began within 20 minutes of the previous engine shutdown.
b) Warm Starts: Trips which began after the engine had been shut down between 21 and 630 minutes.
c) Cold Starts: All first trips of the day and trips which began after the engine had been shut down for at least 631 minutes.

At first glance, the distribution for warm starts seems quite broad. It seems unrealistic that the engine would still be warm after cooling down for 630 minutes (10.5 hours). The basis for this distribution is the ADVISOR engine cool-down model shown in Figure B2.

This model shows that even at 12 hours cool-down time, the engine still retains some heat and emissions are significantly lower than emissions at ambient temperature.

To maintain the integrity of the model and without an alternative engine cool-down model to turn to, this ADVISOR engine cool-down model was used to determine how to divide engine starts into Hot, Warm and Cold starts. The authors recognize that the ADVISOR engine cool-down function may be flawed at the longer time intervals. Sensitivities were done to assess the impact of potentially more realistic cool-down functions at the longer time intervals. The effect of such sensitivities was not significant on the overall results of the model.

D) Model Engine Start-up Exhaust Emissions

For each group of starts, a table was created of emission rates as a function of mileage from engine start (see Figure B3). These data are simply a tabulated form of the data represented in Figure B2. (Note: an average-speed FUDS cycle was used to convert grams per second to grams per mile.) The first three miles are broken into 12 quarter-mile segments, with assigned amounts of emissions in grams. These miles contain more than 99% of start-up emissions and approximately 95% of all the HC and CO emissions (50% of NOx emissions) for the average 8.7 mile trip. After this point, the engine has reached operating temperature, and all additional miles of the trip generate emissions at the rate shown in the last column (grams per mile).

Hot start emissions were modeled based on a 10-minute engine cool-down period (the median of its distribution). Similarly, warm-start emissions were modeled based on a 180 minute cool-down period. Cold-start emissions were modeled based on an “ambient” start” (20C).

E) Model System Vehicle Exhaust Emissions

Finally, each trip in the NPTS data is analyzed to determine its emissions. The following analysis is run for the baseline HEV and BOEV vehicles of various battery-only ranges. For each particular vehicle identified in the database, all its trips are analyzed in chronological order in the following manner:

a) Determine if the vehicle battery-only range has been exceeded, taking into account all previous trips for that day.
b) Calculate the amount of vehicle miles driven on this trip with the APU operating.
c) If the APU is turned on, determine the type of engine start (hot, warm or cold) based on the engine cool-down time since the previous engine start.
d) Based on the above two factors, calculate the emissions for the trip using the “look-up” table in Figure B3.

The model is run for various HEV and BOEV battery-only ranges to provide the vehicle emission results shown in Figures 12-14.

2. Compare the Continuous HEV to Other Control Strategies.

The continuous mode HEV design has been used as a baseline to assess the benefits of HEVs broadly. The following five designs were assessed:

1) Charge-sustaining continuous series HEV (baseline)

2) Charge-sustaining Mitsubishi series HEV[+]

3) Charge-sustaining thermostat series HEV

4) Charge-depleting series HEV

5) Charge-depleting parallel HEV

Figures B4-B6 outline the key aspects of each of the HEV control strategies.

The HEV computer simulation model ADVISOR, developed by NREL, was used to compare control strategies. The same vehicle, APU, battery pack and electric motor were modeled for all strategies. The basic vehicle is 1500 kg with a 300 kg lead-acid battery pack and an APU using a GEO Metro engine. An electrically-heated catalyst was modeled for all control strategies to reduce cold-start emissions.

The fuel-efficiency map of the GEO Metro engine is shown in Figure B7. The most fuel-efficient operating point occurs in the region centered around the point with coordinates 350 rad/s engine speed and 55 Nm engine torque.

The maps of the tail-pipe emissions are shown for NOx, HC, and CO as Figures B8, B9 and B10. These maps were generated by combining the hot engine-out emissions with the hot 3-way catalytic converter efficiency maps (see Figures B11, B12, B13, B14, B15, B16). Lowest emissions occur in the regions with the lightest shading; highest emissions occur in the darkest regions.

The control strategies were compared based on the FTP driving cycle. Each charge-sustaining strategy was set such that the battery state-of-charge at the end of the driving cycle was the same as at the beginning. Thus, each strategy was compared based on its use of energy from the APU. The charge-depleting series vehicle was allowed to lower its SOC since it is a mission-limited vehicle and is therefore paired with an ACV.

The basic input variables for all the simulations are shown in Figure B17 and they are the same for each control strategy. The engine operating points for speed and torque for each series HEV control strategy were selected to minimize the emissions of NOx, HC and CO, that is, to reach ULEV levels or below for all three pollutants. The operating points chosen are shown in Table B2. The continuous mode emissions were then used as a baseline and all the other modes were scaled as a function of the continuous mode levels

Table B2 - Engine Operating and Control Parameters

Variables	Continuous	Mitsubishi	Thermostat	Charge Depleting	Parallel
APU sp (rad/s)	231.69	243.69	292.5	146.25	NA
APU trq (Nm)	32	39	67.47	33.73	NA
APU sp scale	1	1	1	0.5	0.7
APU trq scale	1	1	1	0.5	0.7
SOC hi	0.8	0.8	0.634	0.8	0.8

Since the charge sustaining HEVs have the same mission capabilities, there is not a need to compare them at a driver level as is the case with a comparison to BOEVs. However, the series charge-depleting HEV was modeled with an ACV pair due to its limited range.

The results of the simulation analysis are outlined in Table B3 and discussed below.

Table B3 - HEV Simulations - Emissions and Fuel Use Results

	Fuel Use	HC Emissions	CO Emissions	NOx Emissions
Continuous (Baseline)	1.00	1.00	1.00	1.00
Mitsubishi (APU Energy)	0.91	1.50	2.26	0.94
Thermostat (APU Energy)	0.86	0.75	2.13	0.08
Charge Depleting (APU/utility energy)	NA	0.80	1.19	0.84
Charge-Depleting Parallel (APU Energy)	0.71	8.79	253.00	0.19

Continuous

The average power required during the FTP cycle for the test vehicle is 7.414 kW. Thus, an APU operating at 7.414 kW continuously during the entire FTP test would enable the starting and ending battery SOC to be the same, and the APU will have provided 100% of the energy for the test. The battery is used for load leveling and 1) recaptures braking energy, 2) absorbs any surplus power from the APU, and 3) provides peak power for acceleration.

The engine operating point for the continuous model is 32 Nm and 231.96 rad/s. This point provides the necessary 7.414 kW and was chosen to be the optimum point in the engine map for the control of NOx, HC and CO. The curve of possible torque/speed points that would yield this power level is shown on Figures B8-B10. Note from Figure B7 that torque levels below about 30 Nm should be avoided because fuel economy would fall too low. Note from Figures B8 and B9 that for this desired power level of 7.414 kW it is not possible to select an operating point that yields lowest NOx and lowest HC at the same time. As we shall see in the next section, there is such an operating point for the Thermostat Mode.

Thermostat

The operating point for the Thermostat Mode was chosen to be the optimum point in the engine map for the control of NOx, HC and CO. The point, at 67.47 Nm and 292.5 rad/s, results in 19.735 kW and corresponds to a point close to the most fuel-efficient operating region of the engine.

The APU is operated at this power level for 696 seconds and then shut down for the remainder of the test. This duration results in a battery SOC at the end of the test equal to the SOC at the beginning of the test.

When compared to the Continuous Mode control strategy, the emissions in the Thermostat Mode are lower for HC and NOx, and the fuel economy is higher (see Table B3). This result illustrates the benefit of operating an engine at its ideal operating point so that emissions can be reduced to their lowest levels. At this ideal operating point, engine fuel efficiency can be maintained at near maximum levels. In the Thermostat Mode, the increased charge/discharge losses in the energy storage system are more than off-set by the improved engine efficiency.

Mitsubishi

The APU operates at a steady speed and load, but the APU is shut down each time the vehicle slows to a stop. The APU is restarted each time the vehicle resumes speed. The power level of 9.504 kW was chosen so that the battery SOC at the end of the test was equal to the SOC at the beginning.

The operating point of 243.69 rad/s and 39 Nm was chosen as he optimum point in the engine map for the control of NOx, HC and CO that also would provide the specified 9.504 kW of power. The curve of possible torque/speed points that would yield this power level is shown on Figures B7-B10.

Fuel economy in this mode is somewhat better than for the Continuous Mode but still not as good as with the Thermostat Mode. HC and CO emissions are somewhat higher and NOx somewhat lower than in the Continuous Mode.

Parallel

The key benefit of the parallel mode is that the APU operates only at vehicle speeds above the threshold; thus, operation of the engine at low speeds and low torque can be avoided.

As can be seen in Table B3, HC and CO emissions are not as low as for any of the series HEV modes. Fuel efficiency, however, is maximum, reflecting the fact that the inefficient low-speed and idling ICE operating modes have been displaced by the electric motor. Because this is a charge-depleting mode, fuel economy will be somewhat poorer when a correction factor is added to compensate for the net reduction in SOC.

Charge-depleting Series Mode

Due to its limited range, the charge-depleting HEV is modeled assuming that an ACV would be used for the longer trips. It is assumed that the driver would not plan to operate the vehicle in the "limp-home" mode and instead would use an ACV on days when the expected travel distance was beyond the range of the Charge-depleting HEV. The Charge-depleting HEV was modeled to have a battery-only range of 25 miles and a total extended range with the APU of 65 miles. This charge-depleting HEV with a companion ACV is then compared with a 25-mile battery-range Continuous Mode HEV to generate the scalar factors shown in Table B3. The comparison is done in the same manner as was done with the BOEV as is outlined in this report.

As would be expected, emissions are comparable to the emissions in the Continuous Mode control strategy. Were the engine to be down-sized to provide its low (4 kW) power at the ideal operating point in an engine map, it is likely that very low emissions could be obtained (similar to the Thermostat Mode). However, the vehicle would have a limited range, and the vehicle would not be suitable for more high-power sustained travel, such as mountain driving.

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[i] The Mitsubishi operating mode modeled in this study is a simplified simulation based upon Refrence 9; it is not meant to be an exact replication of the Mitsubishi program.

Figure B1 - Original NEVCOR Vehicle Emissions Anlaysis

					EXHAUST EMISSIONS* (metric tons)				ELECTRICITY USE* (gWh)		GASOLINE USE* (millions of gallons)			
Daily Mileage	Annual Drivers (millions)	Cum. % of Total Drivers	Annual Miles (millions)	Cum. % of Total Miles	Pair: Batt.-Only EV/ICV	Hybrid EV	Advanced ICV	1993 ICV	Pair: Batt.-Only EV/ICV	Hybrid EV	Pair: Batt.-Only EV/ICV	Hybrid EV	Advanced ICV	1993 ICV
0 — 5	5,502	16.1%	13,615	1.2%	0	0	545	5,582	2,042	2,042	0	0	272	504
5 — 15	8,685	41.6%	81,973	8.8%	0	0	3,279	33,609	12,296	12,296	0	0	1,639	3,036
15 — 25	5,891	58.9%	115,642	19.4%	0	0	4,626	47,413	17,346	17,346	0	0	2,313	4,283
25 — 35	3,940	70.5%	116,245	30.0%	0	0	4,650	47,660	17,437	17,437	0	0	2,325	4,305
35 — 45	2,737	78.5%	107,557	39.9%	0	0	4,302	44,098	16,134	16,134	0	0	2,151	3,984
45 — 55	1,805	83.8%	88,900	48.0%	0	0	3,556	36,449	13,335	13,335	0	0	1,778	3,293
55 — 65	1,467	88.1%	87,175	56.0%	0	0	3,487	35,742	13,076	13,076	0	0	1,744	3,229
65 — 75	908	90.7%	63,217	61.8%	0	169	2,529	25,919	9,483	8,849	0	84	1,264	2,341
75 — 85	675	92.7%	53,553	66.7%	0	387	2,142	21,957	8,033	6,582	0	194	1,071	1,983
85 — 95	591	94.5%	52,951	71.6%	0	580	2,118	21,710	7,943	5,766	0	290	1,059	1,961
95 — 105	453	95.8%	45,132	75.7%	1,805	627	1,805	18,504	0	4,417	903	314	903	1,672
105 — 115	233	96.5%	25,543	78.1%	1,022	415	1,022	10,473	0	2,274	511	208	511	946
115 — 125	209	97.1%	24,950	80.3%	998	455	998	10,230	0	2,037	499	227	499	924
125 — 135	138	97.5%	17,804	82.0%	712	353	712	7,299	0	1,346	356	177	356	659
135 — 145	92	97.8%	12,856	83.2%	514	274	514	5,271	0	900	257	137	257	476
145 — 155	131	98.1%	19,676	85.0%	787	445	787	8,067	0	1,281	394	223	394	729
> 155	633	100.0%	164,064	100.0%	6,563	4,918	6,563	67,266	0	6,168	3,281	2,459	3,281	6,076
Totals	34,090	100.0%	1,090,853	100.0%	12,401	**8,625**	43,634	447,250	117,124	**131,285**	6,201	**4,312**	21,817	40,402
***ASSUMPTIONS FOR THE ABOVE**														
Average NMOG Emissions (grams/mile)					0.04	0.04	0.04	0.41						
Maximum usable range battery power alone (mi)					95	65	0	0	95	65				
Kilowatt hours per mile (average driving conditions)									0.15	0.15				
Miles per Gallon when Using Gasoline											50	50	50	27
Overall Miles per Gallon											176	253	50	27
Annual Gasoline Cost (billions of 1993 dollars) @ $1.30/gal											$8.1	$5.6	$28.4	$52.5

Figure B2 - Vehicle HC Emissions Based on Engine Cool Down Time

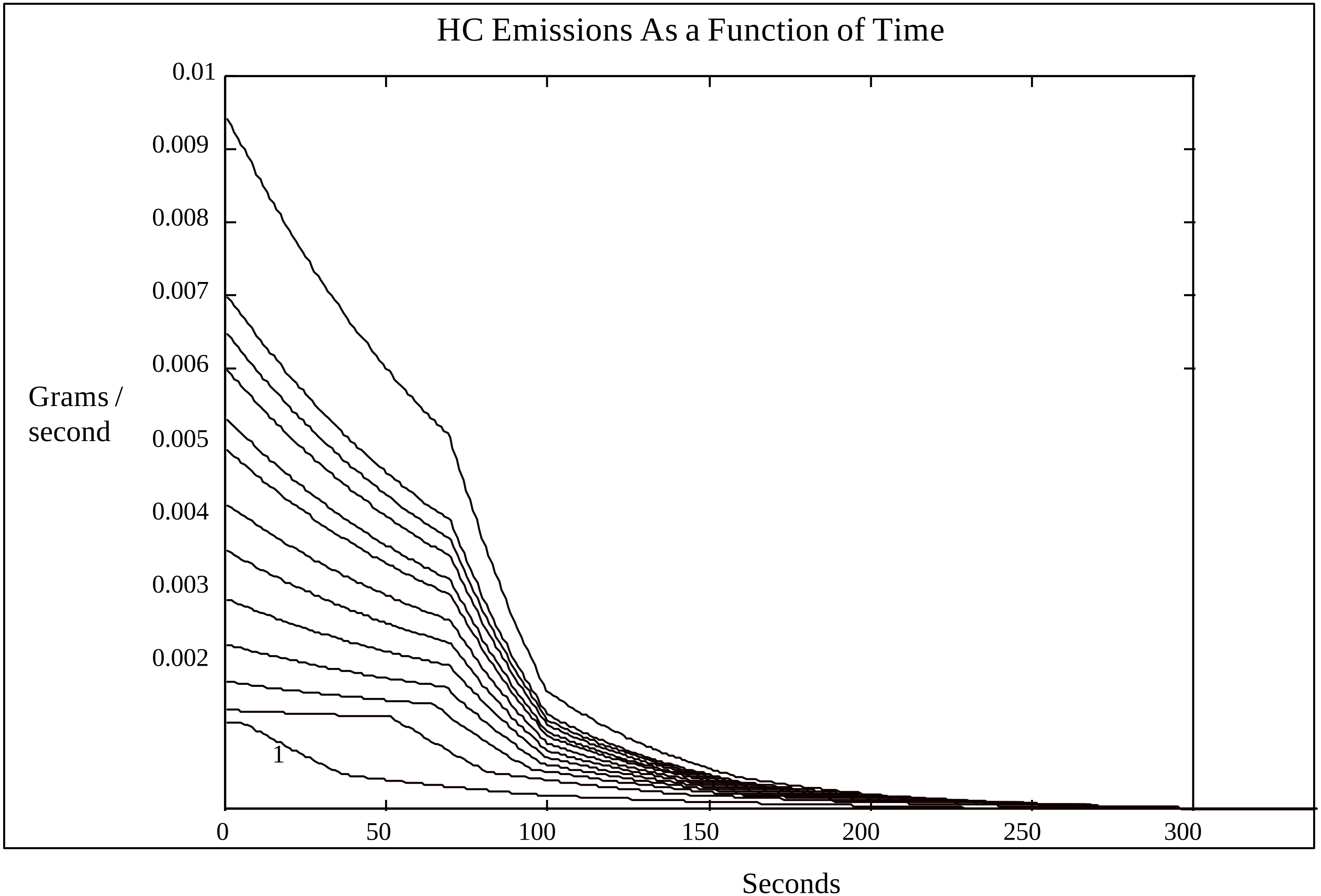

Figure B3 - Look-up Table of Vehicle Emissions

ULEV Vehicle													
HOT				1 mile				2 miles				3 miles	Continous
HC	0.00060	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00210
CO	0.02060	0.01980	0.01980	0.01980	0.01980	0.01980	0.01980	0.01980	0.01980	0.01980	0.01980	0.01980	0.08070
NOx	0.03230	0.03220	0.03220	0.03220	0.03220	0.03220	0.03220	0.03220	0.03220	0.03220	0.03220	0.03220	0.13150
WARM				1 mile				2 miles				3 miles	Continuous
HC	0.03490	0.01390	0.00710	0.00370	0.00160	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00210
CO	1.08900	0.25410	0.13430	0.07640	0.03950	0.02020	0.01980	0.01980	0.01980	0.01980	0.01980	0.01980	0.08070
NOx	0.24900	0.06000	0.03870	0.03720	0.03400	0.03230	0.03220	0.03220	0.03220	0.03220	0.03220	0.03220	0.13150
COLD				1 mile				2 miles				3 miles	Continuous
HC	0.34850	0.21440	0.06060	0.02220	0.00910	0.00370	0.00100	0.00060	0.00060	0.00050	0.00050	0.00050	0.00210
CO	16.63770	9.40470	1.38600	0.45690	0.19280	0.08550	0.03340	0.02400	0.02230	0.02130	0.02070	0.02030	0.08080
NOx	0.70550	0.45800	0.08980	0.04360	0.03830	0.03530	0.03270	0.03220	0.03220	0.03220	0.03220	0.03220	0.13150

Figure B4 - Continuous and Mitsubishi HEV Simulation - Control Strategies

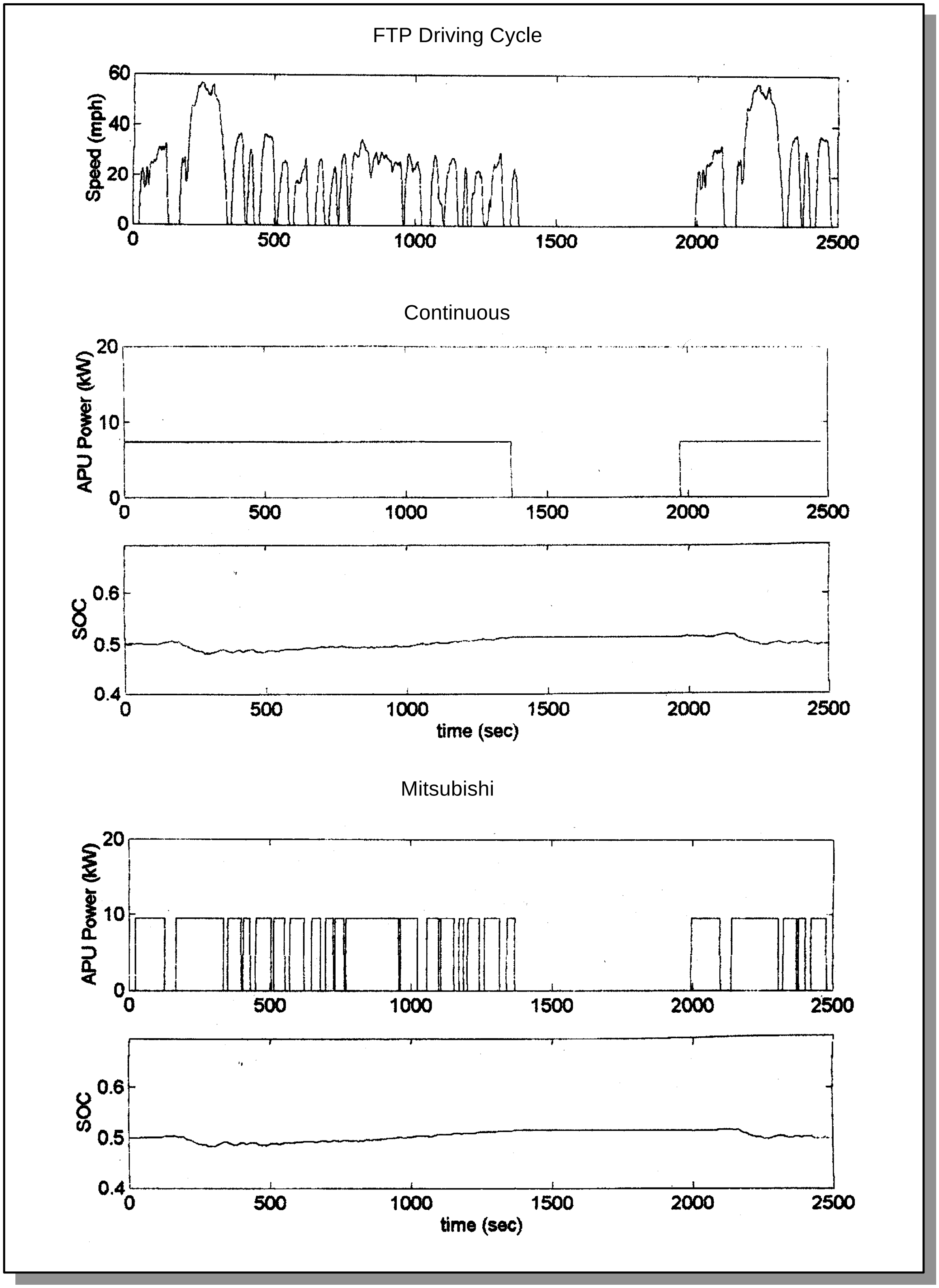

Figure B5 - Thermostat and Charge Depleting HEV Simulation - Control Strategies

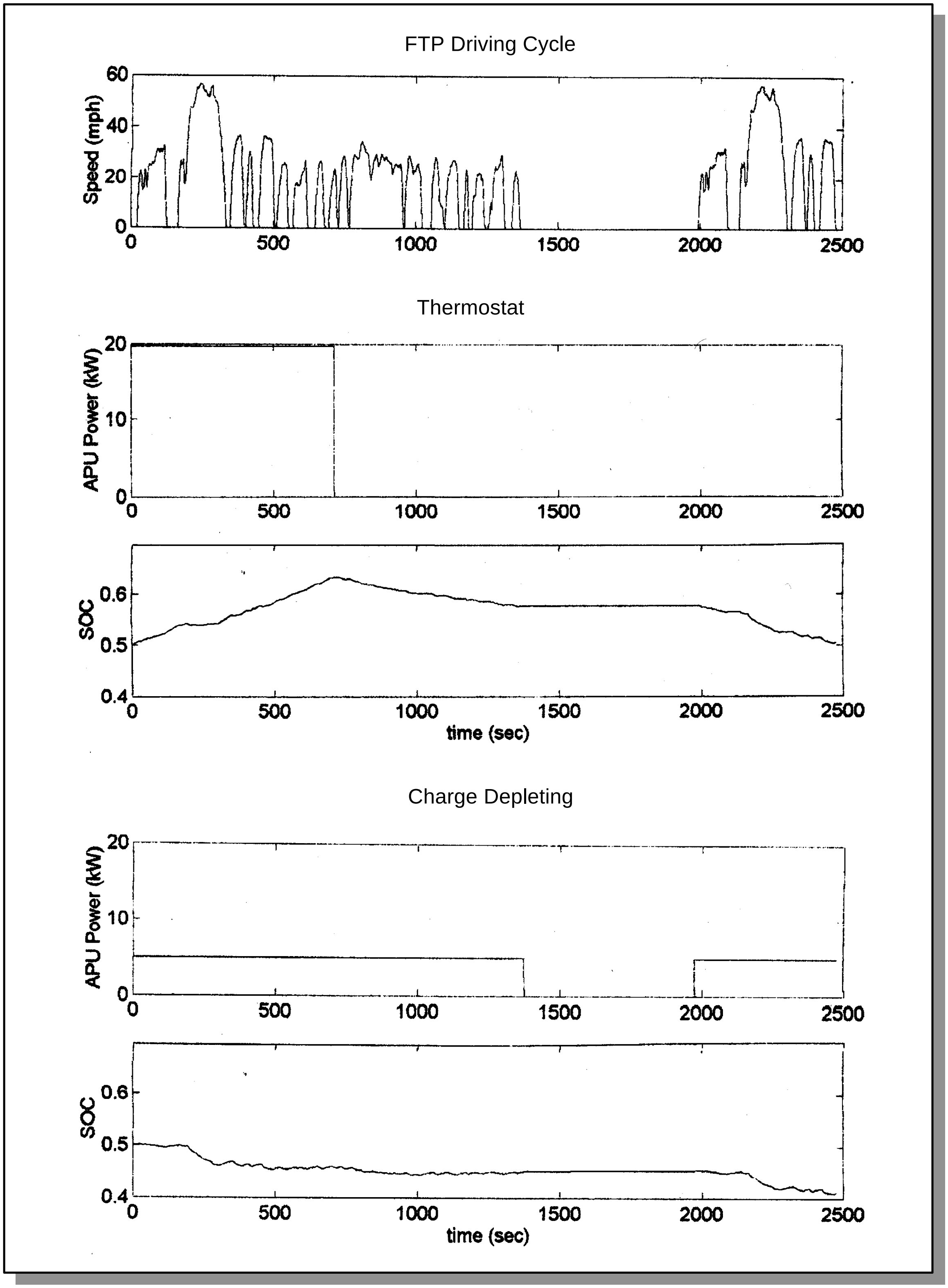

Figure B6 - Parallel HEV Simulation - Control Strategy

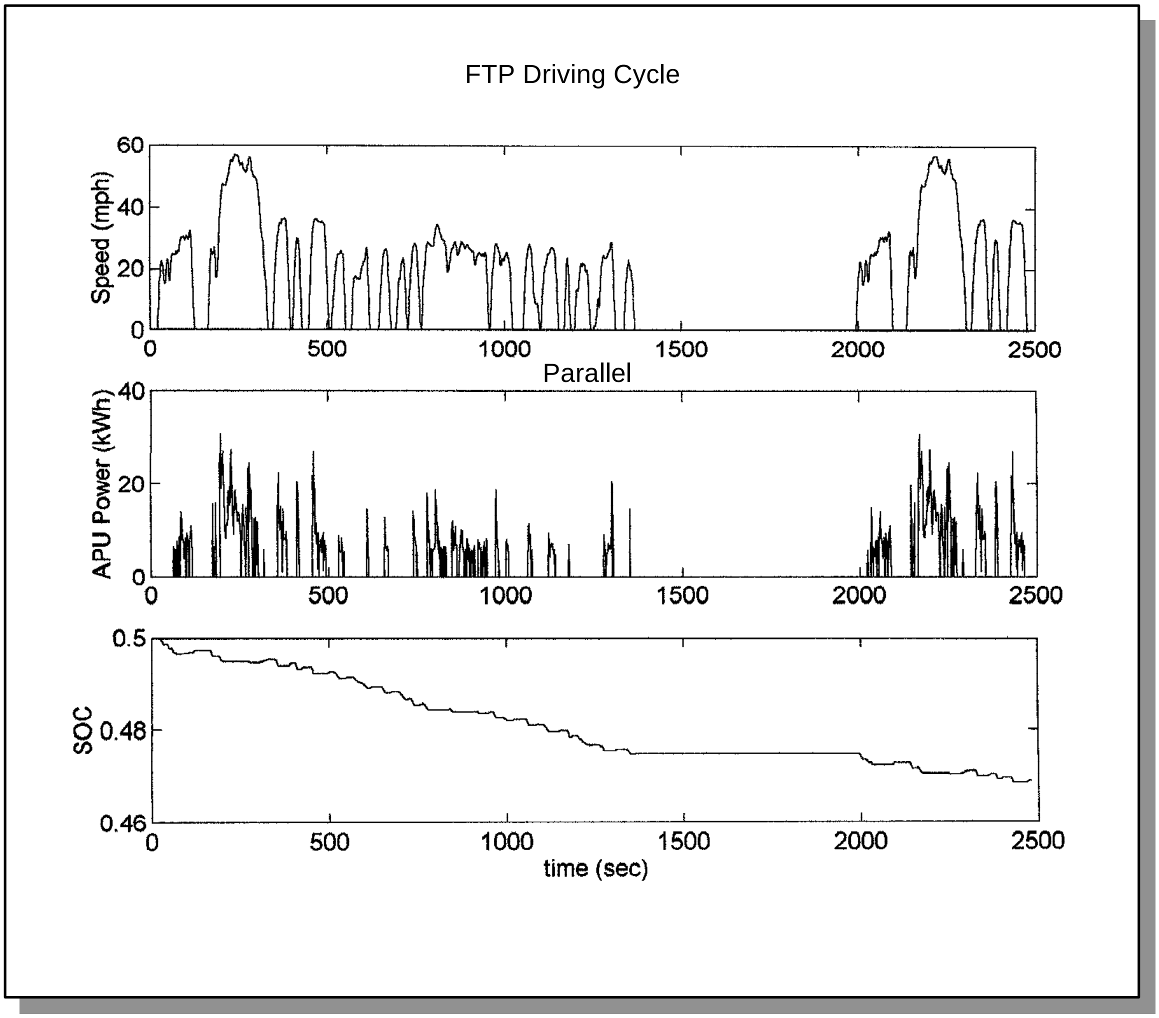

Figure B7 - GEO Metro Engine - Fuel Efficiency

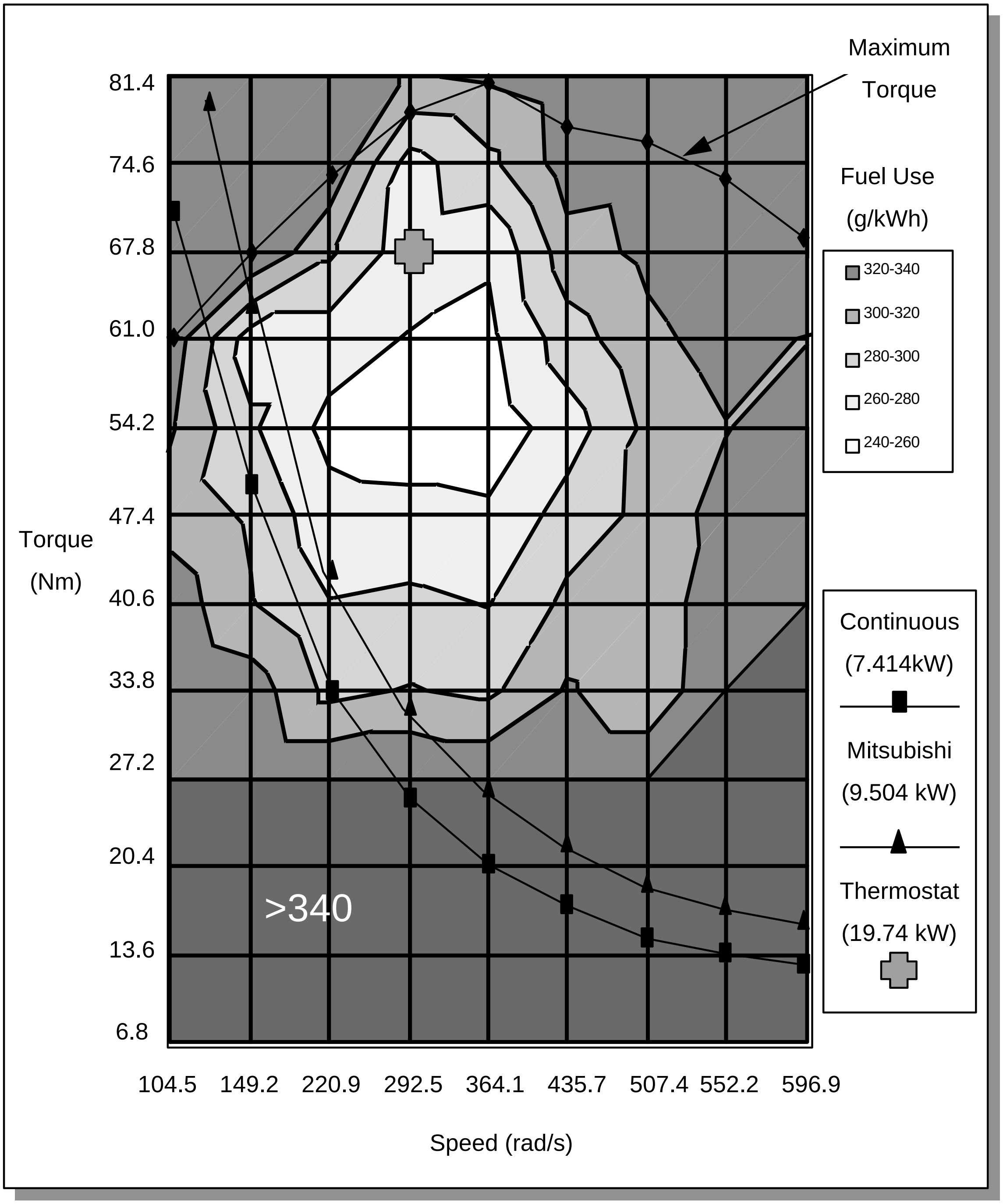

Figure B8 - GEO Metro Engine - Hot Running Tailpipe Nox Emissions

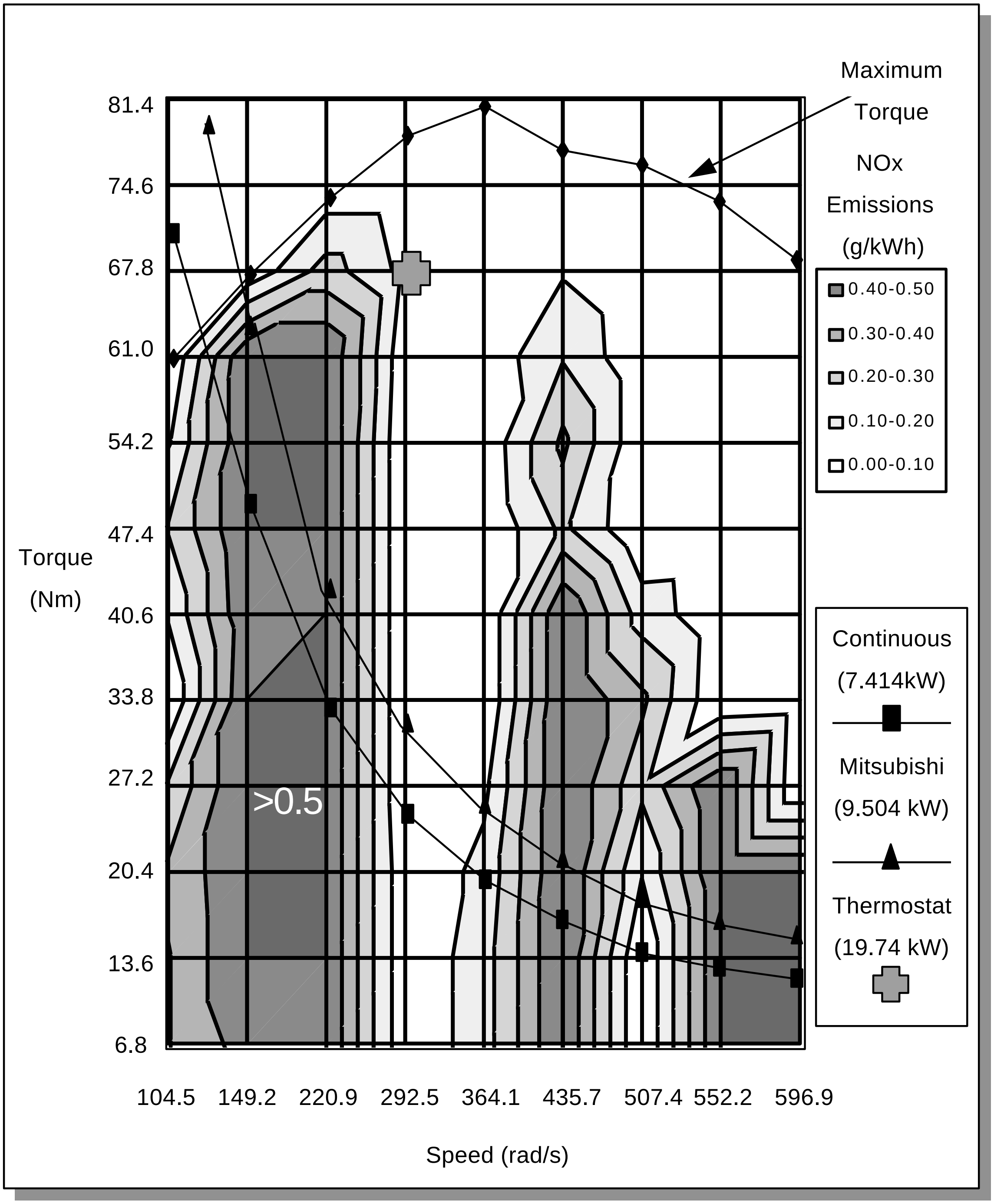

Figure B9 - GEO Metro Engine - Hot Running Tailpipe HC Emissions

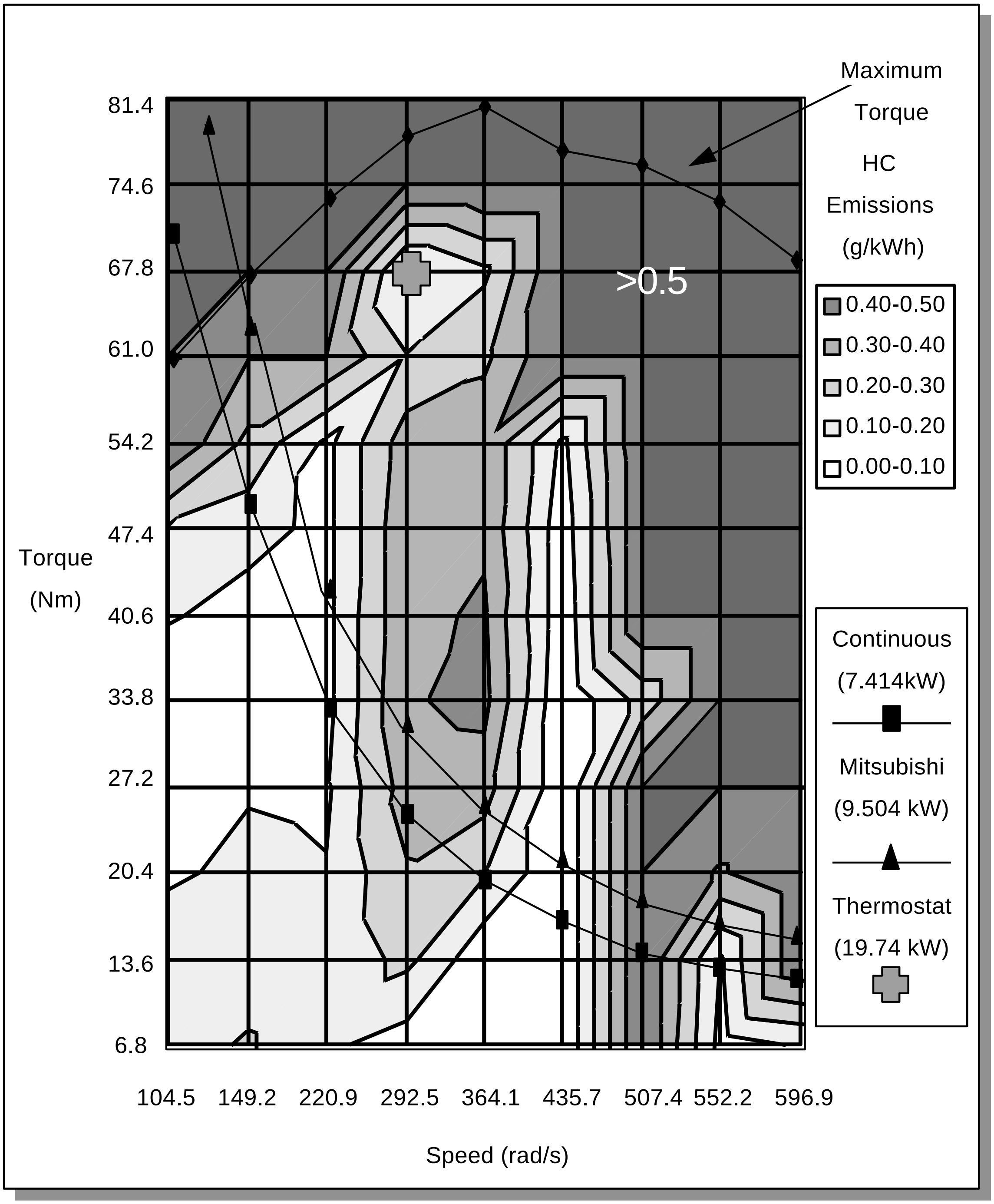

Figure B10 - GEO Metro Engine - Hot Running Tailpipe CO Emissions

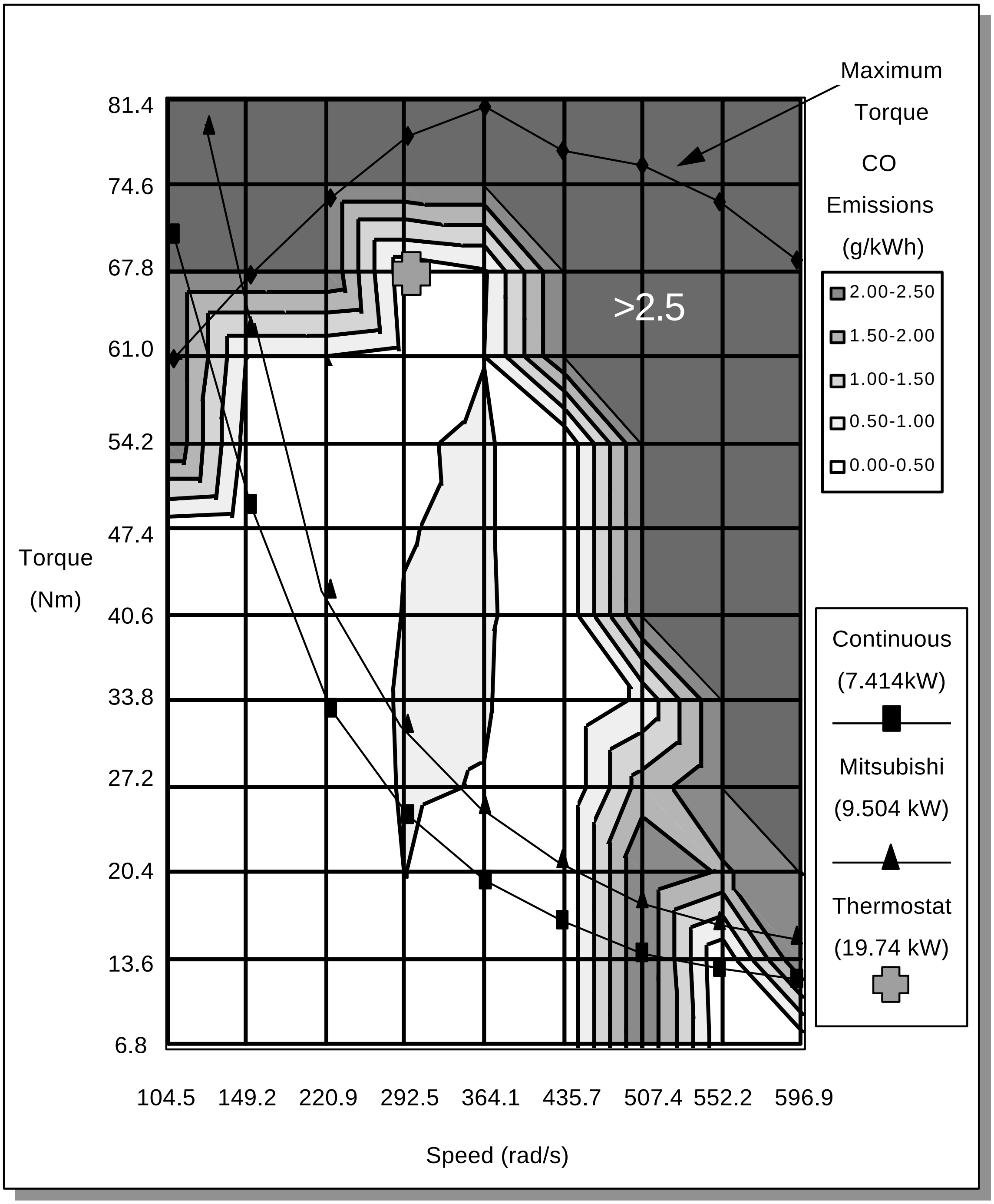

Figure B11 - GEO Metro Engine - Hot Running Engine-Out NOx Emissions

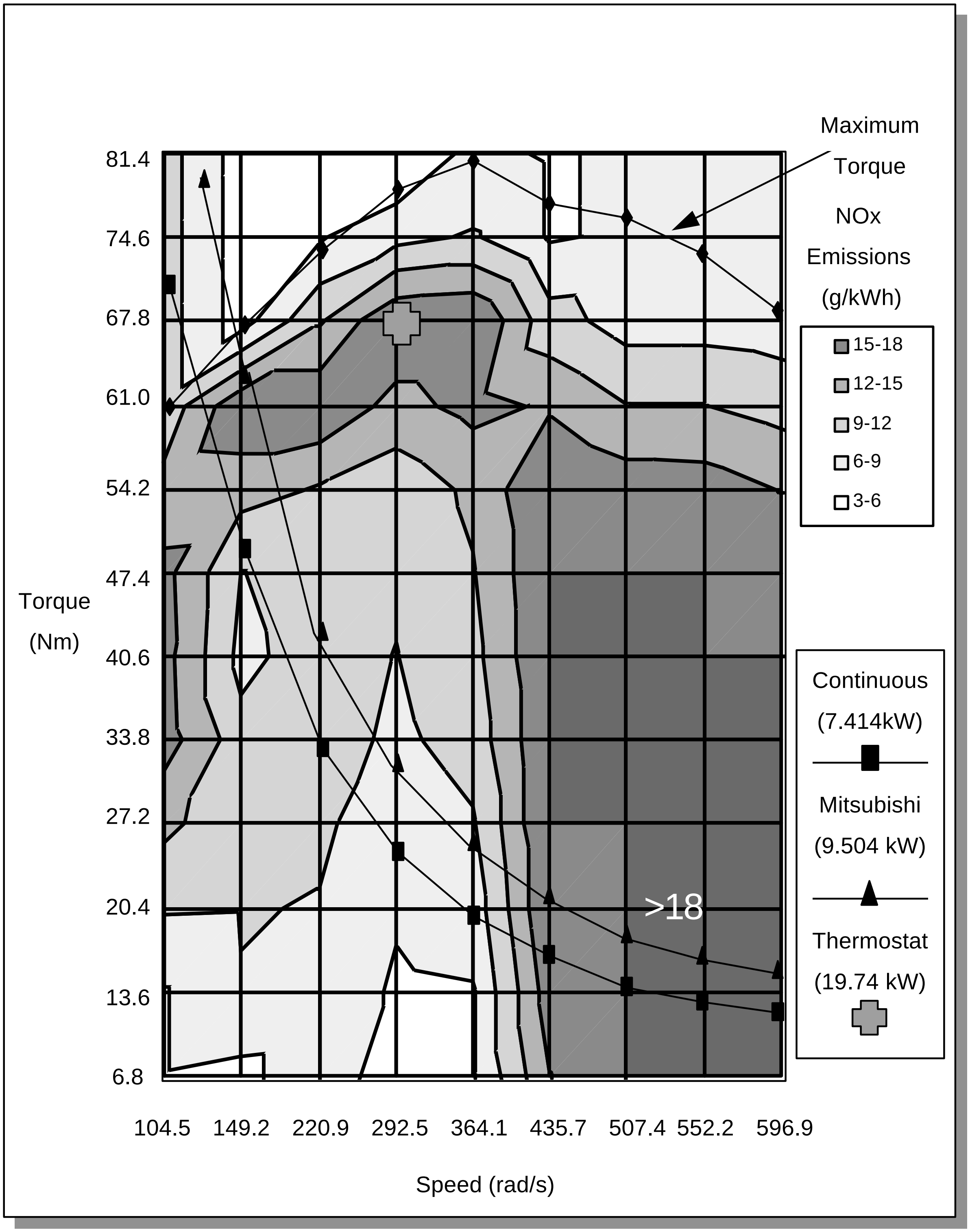

Figure B12 - GEO Metro Engine - Hot Running Engine-Out HC Emissions

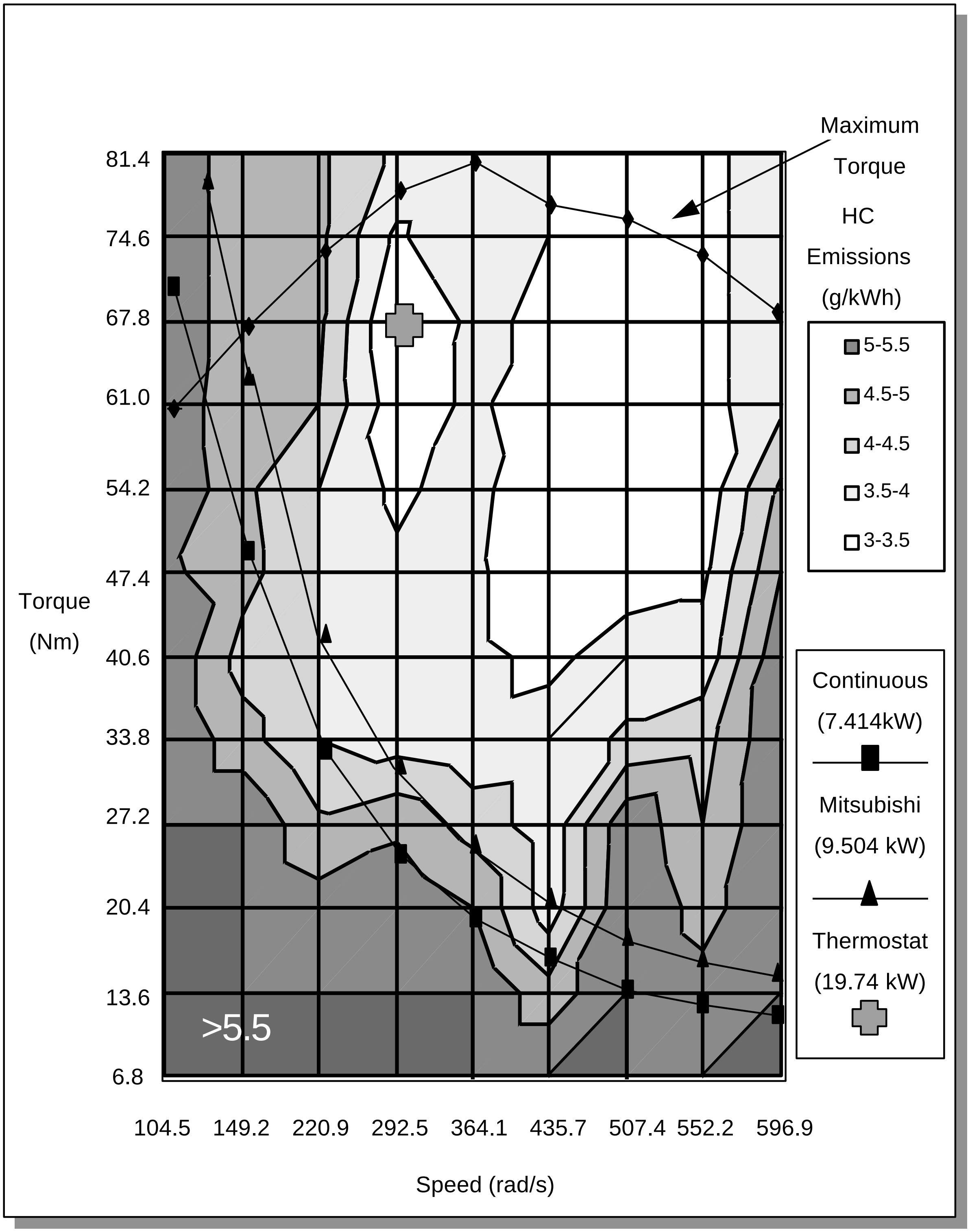

Figure B13 - GEO Metro Engine - Hot Running Engine-Out CO Emissions

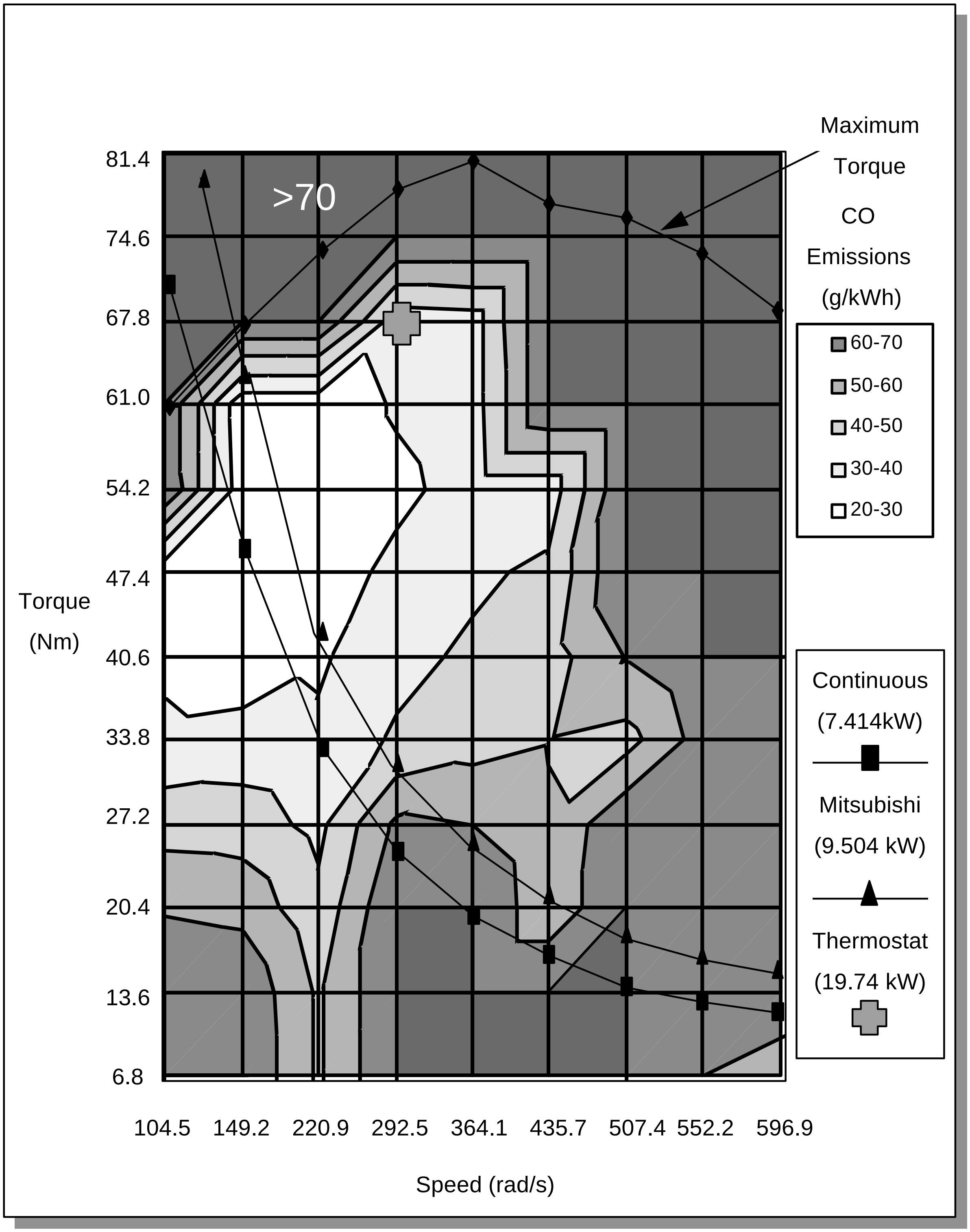

Figure B14 - GEO Metro Engine - Catalytic Converter Efficiency - NOx

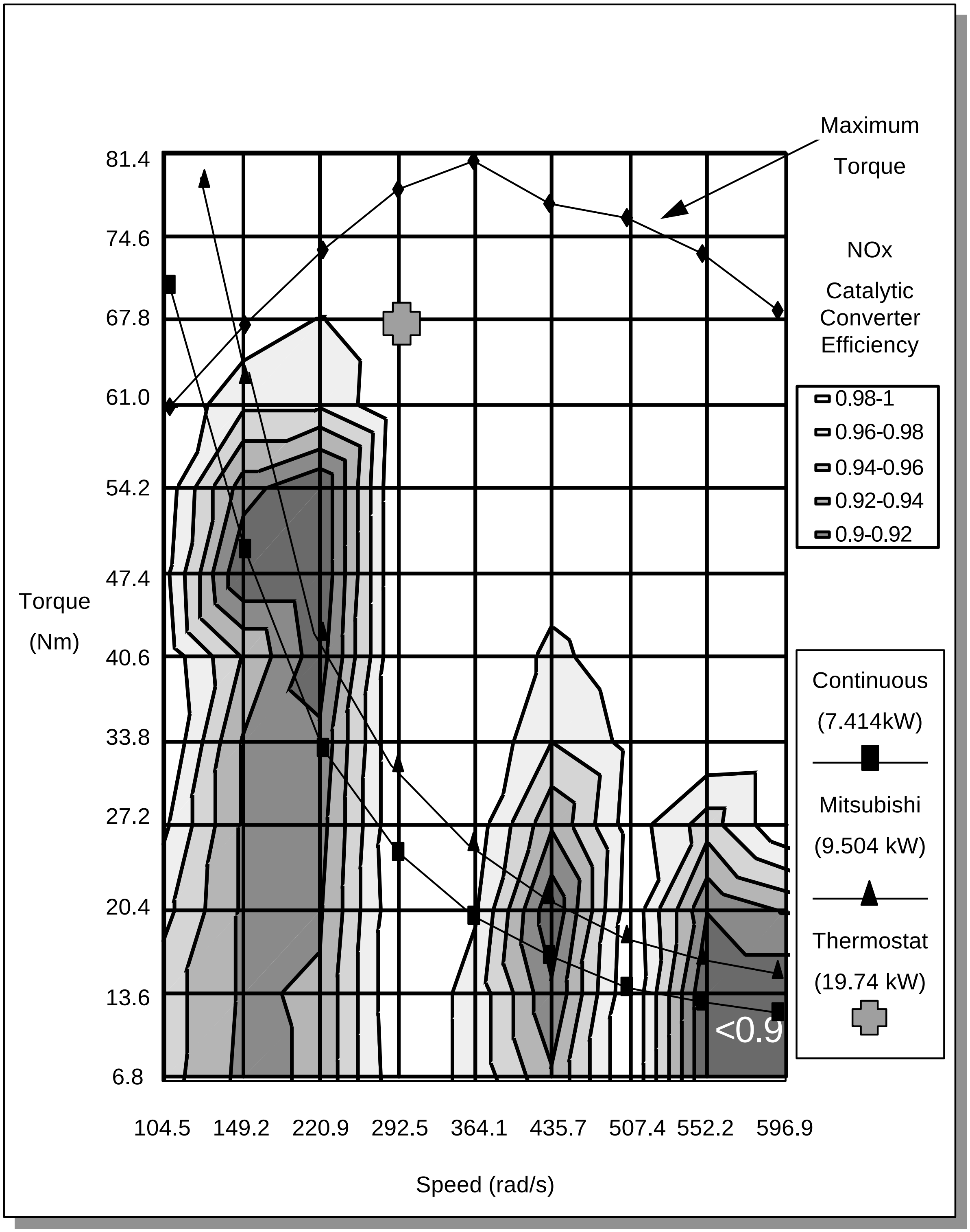

Figure B15 - GEO Metro Engine - Catalytic Converter Efficiency - HC

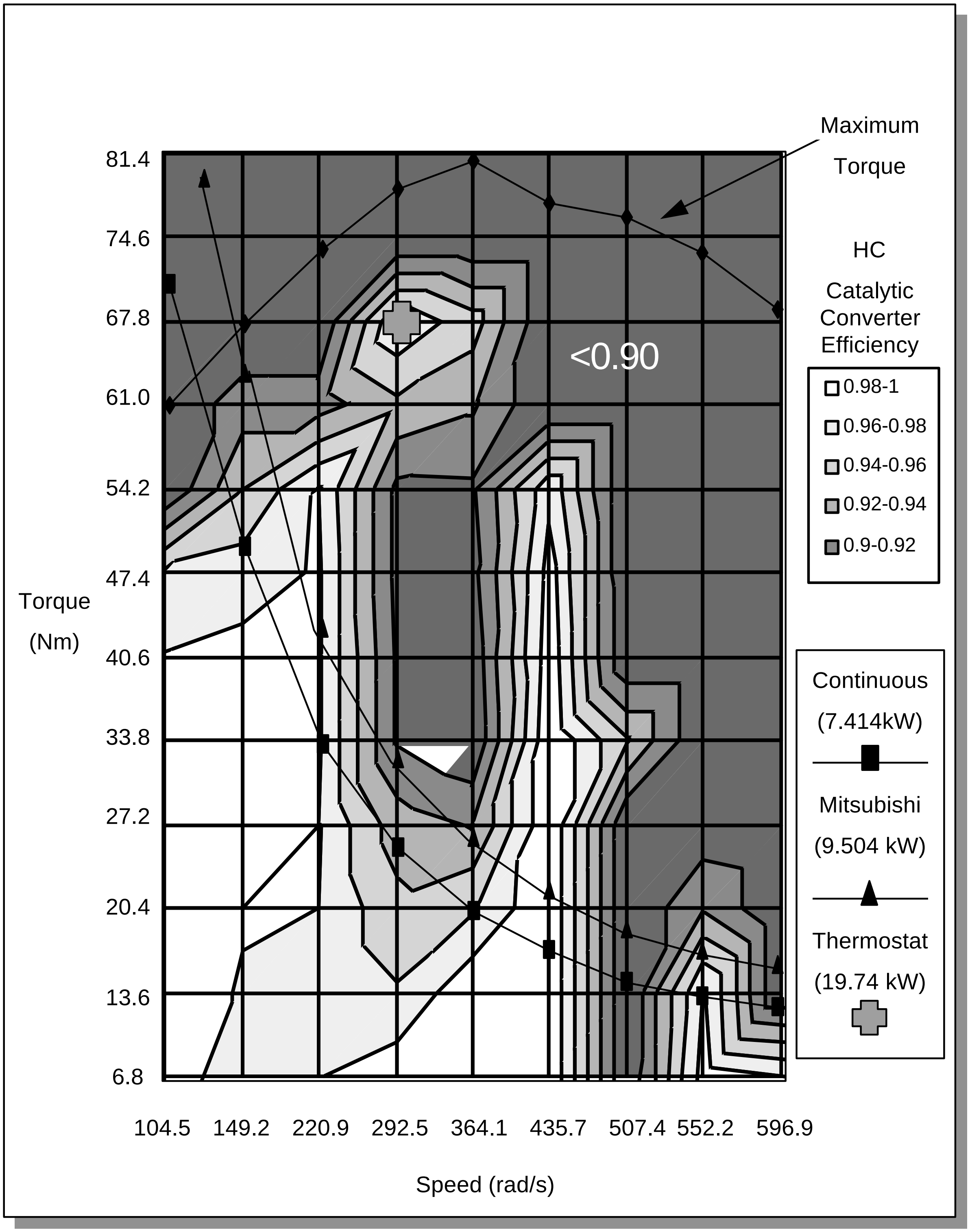

Figure B16 - GEO Metro Engine - Catalytic Converter Efficiency - CO

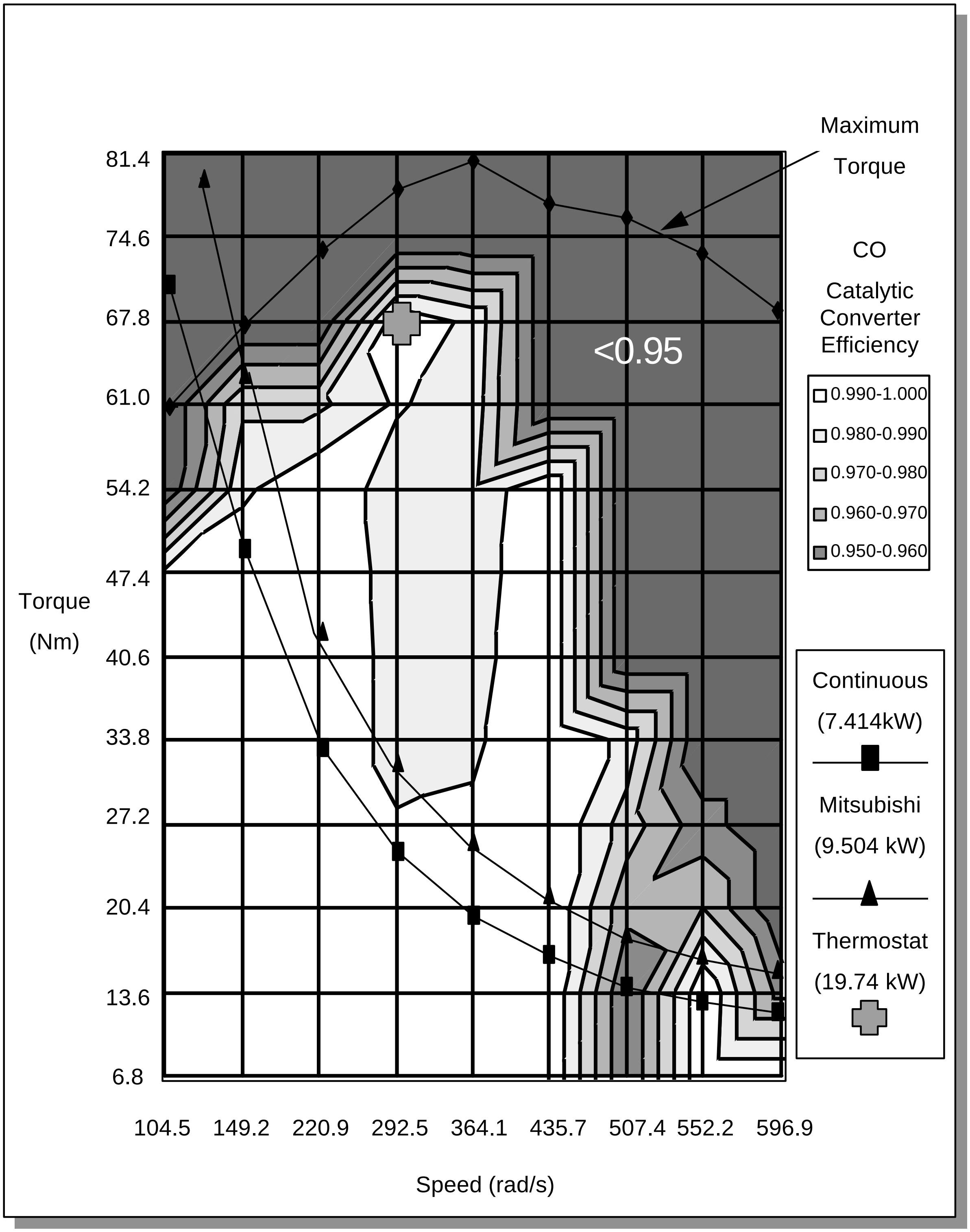

Figure B17 - Basic Assumptions for HEV Simulation Runs in ADVISOR

TRANSMISSION

m5spd_t	
eta_tconverter=1;	torque converter efficiency
tx_shiftdelay=0;	

APU

geo1l_a	fuel and emissions maps
APU_trqscale=1;	modify the maximum torque and the torque points in the maps
APU_spdscale=1;	modify the maximum speed and the speed points in the maps
fuel_mden=737;	g/L, mass density of fuel

GENERATOR

sr180p_g	efficiency map
gen_trqscale=1;	modify the maximum torque and the torque points in the map
gen_spdscale=1;	modify the maximum speed and the speed points in the map

EMISSIONS CALCS

cat1	temperature dependence of catalyst
Tcatmax=650;	deg. C, maximum catalyst temperature
Tcatinit=650;	deg. C, initial catalyst temperature
TECss=95;	% deg. C, maximum engine coolant temperature
TECinit=20;	% deg. C, initial engine coolant temperature
Tamb=20;	% deg. C, ambient temperature

ROAD LOAD & MISCELLANY

fuds_c	speed trace, and key on
gravity=9.81;	m/s^2
CD=.25;	
Area=2;	m^2
Crr=0.0105;	
Crr1=0;	s/m
Crr2=0;	(s/m)^2
mass=1500;	kg
mipart=50;	kg, mass equivalent of inertia of rotating parts
rradius=11/12/3.281;	m, rolling radius of tire
rf=.5;	regenerative braking fraction--fraction of braking done by motor
rho=1.2;	kg/m^3
accsry_kW=0;	accessory load
grade=0;	road grade

MOTOR

westng_m	efficiency map, torque envelope
mot_trqscale=1;	modify the maximum torque and the torque points in the map
mot_spdscale=1;	modify the maximum speed and the speed points in the map
mot_inertia=0;	motor inertia gain factor

ENERGY STORAGE

gnb_e	Peukert data, Voc and Rint vs. SOC
ESS_num=10;	number of modules
con_V_min=0.1;	minimum current

CONTROL STRATEGY

SOCinit=0.5;	initial SOC
SOChi= varies;	SOC at which APU is turned off
SOClo= varies;	SOC at which APU is turned on
APU_oppnt_spd= varies;	rad/s, single operating point for the APU
APU_oppnt_trq= varies;	Nm